Introduction – Chris Develder

- Professor at Ghent University since Oct. 2007
  - *Research Interests*: **smart grids**; dimensioning, modeling and optimizing **optical** (grid/cloud) networks; **information retrieval/extraction**
  - Visiting researcher at UC Davis, CA, USA, Jul-Oct. 2007 (optical netw.)
  - Visiting researcher at Columbia Univ., NY, USA, 2013-14 (IR/IE)
- Industry Experience: network planning/design tools
  - OPNET Technologies (now part of Riverbed), 2004-05
- PhD, Ghent University, 2003
  - "Design and analysis of optical packet switching networks"
- More info: http://users.atlantis.ugent.be/cdvelder

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Charging electric vehicles in the smart grid

Kevin Mets, Arun Narayanan, Matthias Strobbe,
Chris Develder

Ghent University – iMinds
Dept. of Information Technology – IBCN

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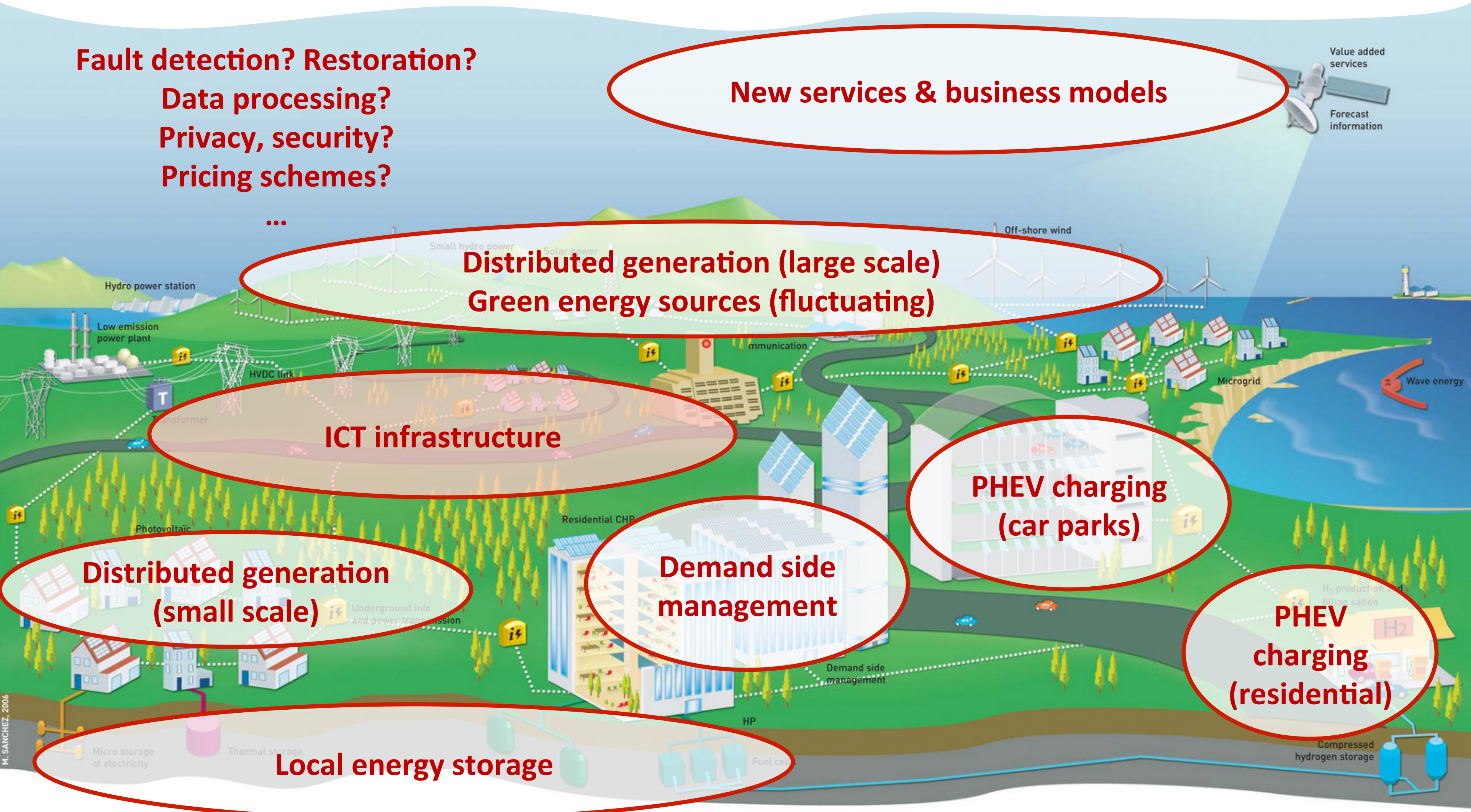
Outline

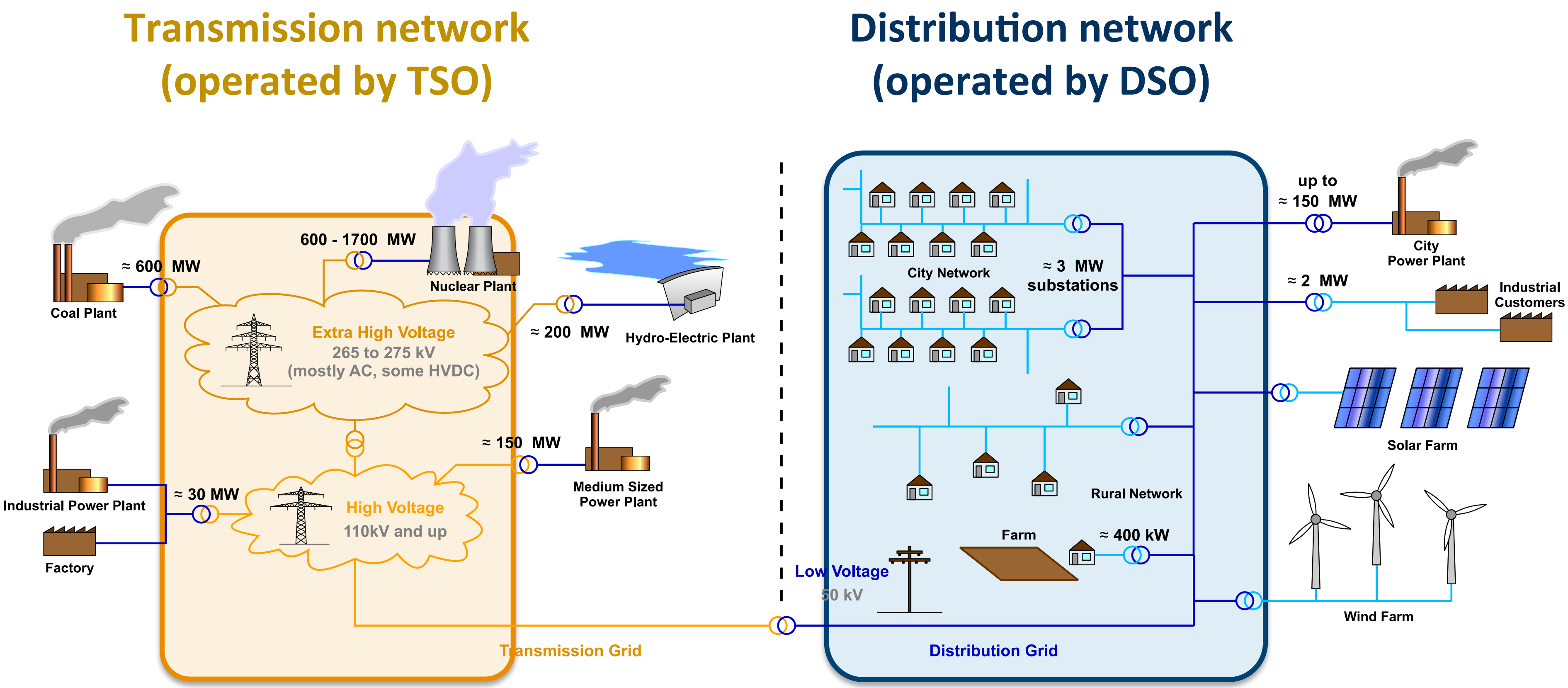
1. Introduction
2. Example 1: Peak shaving
3. Example 2: Wind balancing
4. DR algorithms for EV charging
5. Tools to study EV charging
6. Wrap-up

Smart Grids



C. Develder, et al., "Distributed smart charging of electrical vehicles"

Power grid structure



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Types of electrical vehicles: Key acronyms

- **EV** = all-electrical vehicle, aka **BEV** = battery electrical vehicle
- **HEV** = hybrid EV, includes non-electrical motor (typically ICE)
- **PEV** = plug-in EV, i.e., EV or PHEV
- **PHEV** = plug-in hybrid EV
- **ICE** = internal combustion engine (i.e., burning fuel)
- **EVSE** = electrical vehicle supply equipment, i.e., charging station
- **V2G** = vehicle-to-grid = use battery to deliver power

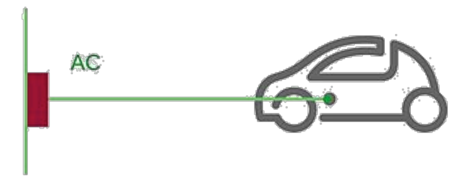
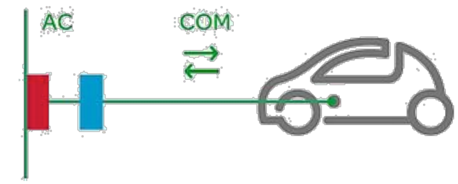
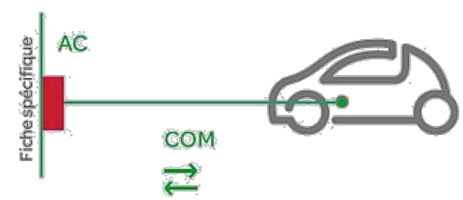
BEV: Nissan Leaf

PHEV: Toyota Prius

EV charging modes

Slow (Mode 1 – Mode 3)

Fast (Mode 3 – Mode 4)

Mode 1	• Domestic AC socket • Single phase • Up to 16A, thus ca. 3.3kW	
Mode 2	• Domestic AC socket, but special cable w/ protection • Single or 3-phase • Higher currents	
Mode 3	• Dedicated AC socket, special cable w/ control (into EVSE) & protection • Single or 3-phase • Up to 55 kW	
Mode 4	• DC socket • External charger, part of EVSE • Up to 400A	

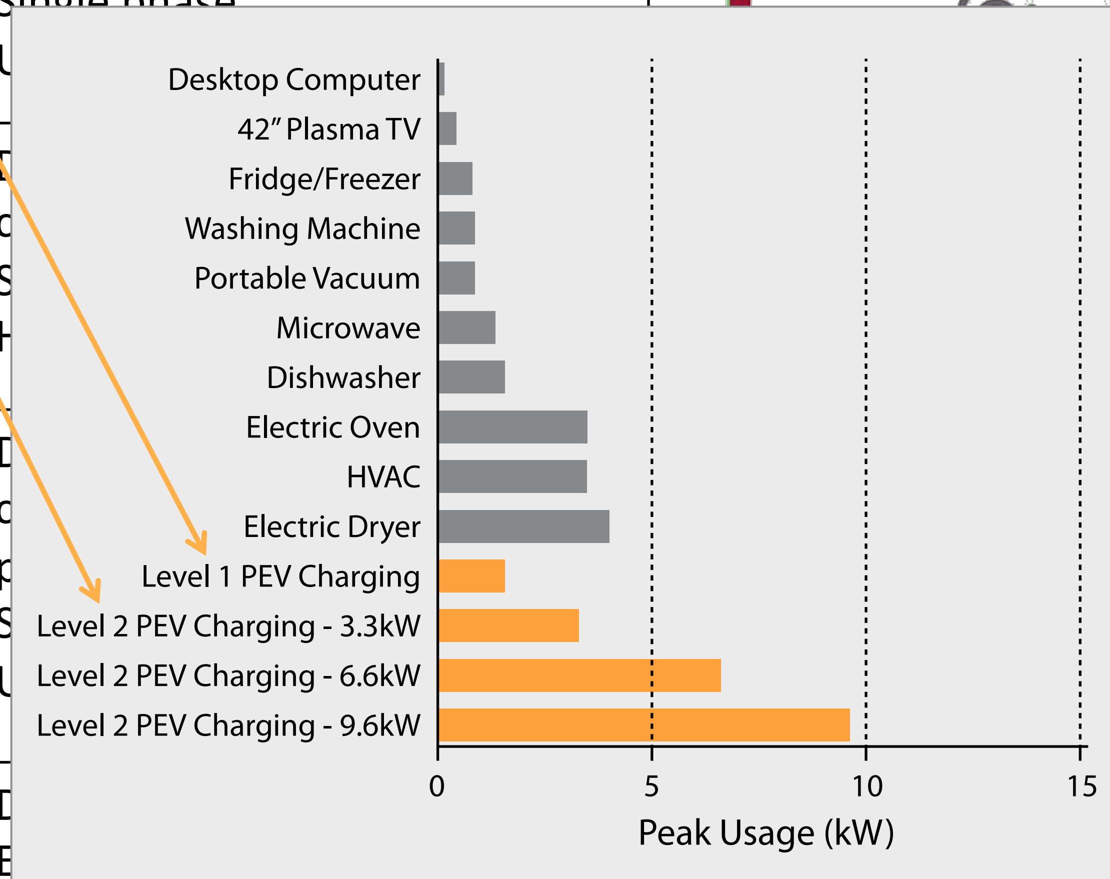
Images: httcp://en.wikipedia.org/wiki/Charging_station

EV charging modes

Slow

Mode 1	• Domestic AC socket • Single phase • U
Mode 2	• D c • S • H
Mode 3	• D c p • S • U
Mode 4	• D • E • Up to 400A

Fast



Images: http://en.wikipedia.org/wiki/Charging_station

EV battery characteristics

	Type	Total battery capacity (kWh)	Note
Chevrolet Volt	PHEV	16.0	10.3 kWh usable (65%)
Toyota Prius Plugin	PHEV	4.4	3.4 kWh usable (77%)
Fisker Karma	PHEV	20.0	
Ford C-Max Energi	PHEV	7.6	
Volvo S60 Plugin	PHEV	12.0	
Honda Accord Plugin	PHEV	6.7	
Mitsubishi Outlander	PHEV	12.0	
Mitsubishi iMIEV	BEV	16.0	
Nissan Leaf	BEV	24.0	20∼22 kWh usable (80∼90%)
Smart electric drive	BEV	16.5	
Volvo C30 DrivE Electric	BEV	24.0	22.7 kWh usable (94%)
Ford Focus Electric	BEV	23.0	19∼20 kWh usable (85%)
BMW i3	BEV	22.0	18.8 kWh usable (85%)
BMW ActivE	BEV	32.0	
Renault Fluence ZE	BEV	22.0	
Renault Zoe	BEV	22.0	
Volkswagen e-UP!	BEV	18.0	

Source: [DeCraemer2014]

EV charging modes: Time to charge

Mode	Charging time for 100km of BEV range	Power supply	Voltage	Max. current
Mode 1	6-8 hours	AC – 1-phase – 3.3 kW	230 V	16 A
	2-3 hours	AC – 3-phase – 10 kW	400 V	16 A
Mode 2	3-4 hours	AC – 1-phase – 7 kW	230 V	32 A
	1-2 hours	AC – 3-phase – 22 kW	400 V	32 A
Mode 3	20-30 minutes	AC – 3-phase – 43 kW	400 V	63 A
Mode 4	20-30 minutes	DC – 50 kW	400-500 V	100-125 A
	10 minutes	DC – 120 kW	300-500 V	300-350 A

IEC 62196-2 Type 2

CHAdeMO

Combo

Communications?

- To achieve external (= power grid) control of the charging process
- Only in ≥ Mode 2

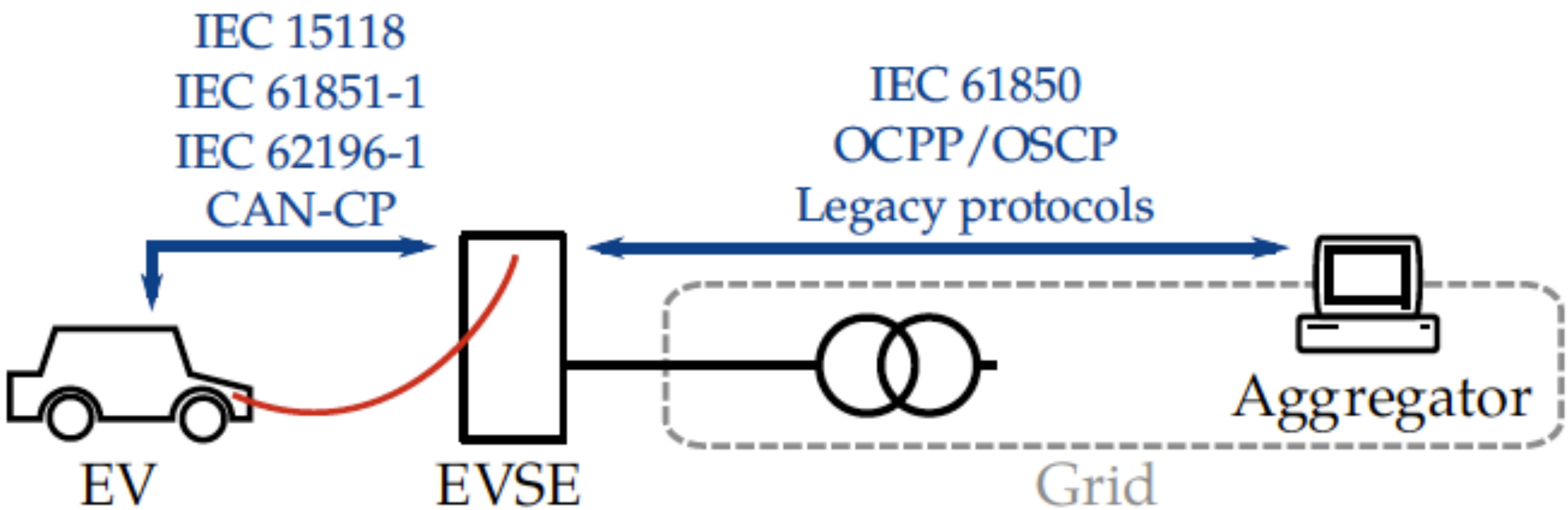


Figure: [K. De Craemer, 2014]

EV charging process

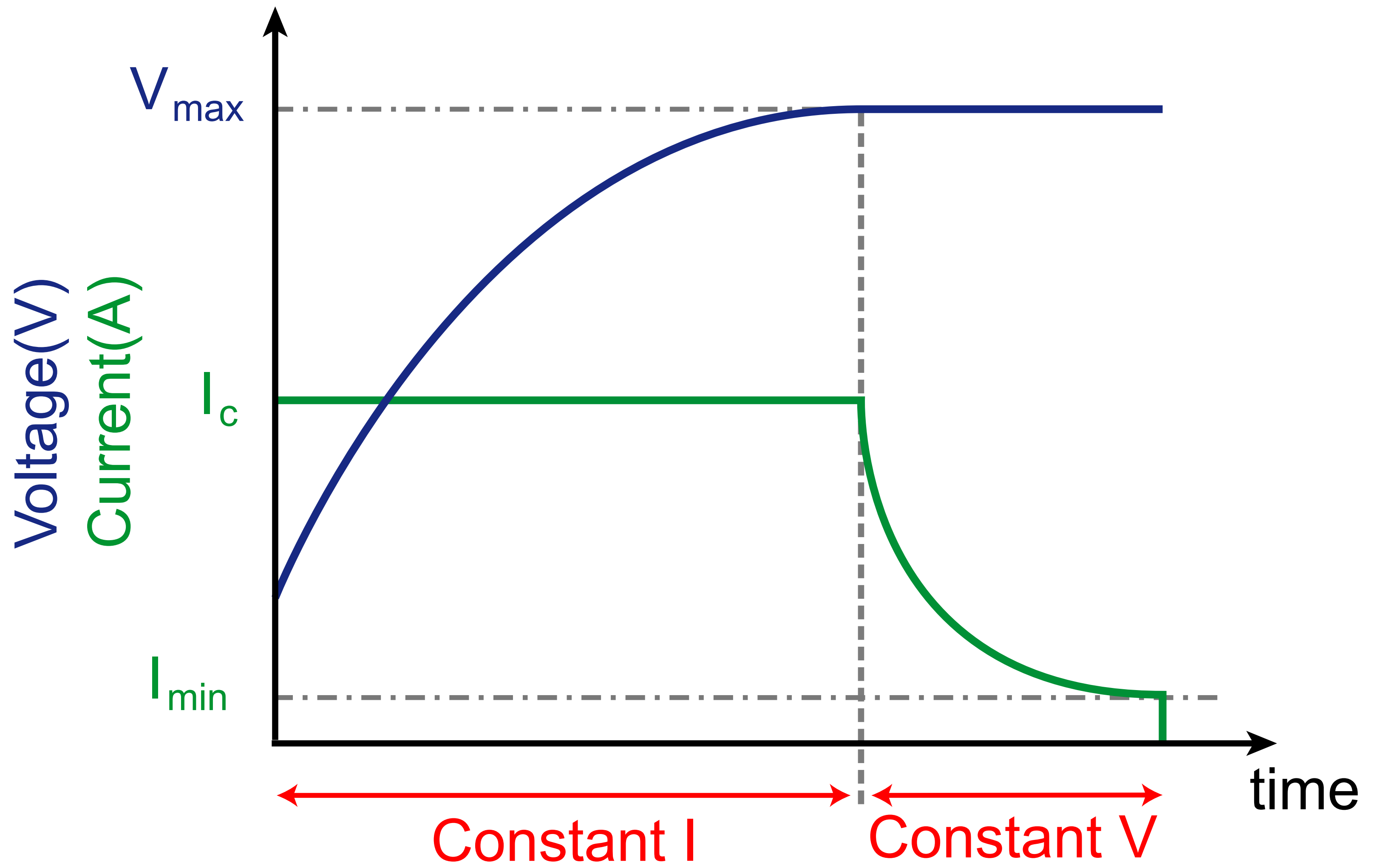


Figure adapted from [K. De Craemer, 2014]

Alternative charging solutions?

- Battery swapping
  - E.g., BetterPlace in Israel, Denmark – filed for bankruptcy
  - Tesla has proprietary system

- Inductive charging
  - Volvo
  - BMW group
  - Fraunhofer
  - …
  - Public transport initiatives

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K. Mets, R. D'hulst and C. Develder, ***"Comparison of intelligent charging algorithms for electric vehicles to reduce peak load and demand variability in a distribution grid"****, J. Commun. Netw., Vol. 14, No. 6, Dec. 2012, pp. 672-681. doi:10.1109/JCN.2012.00033*

Example case study: EV charging

- Research questions:
  1. Impact of (uncontrolled) EV charging in a residential environment?
  2. Minimal impact on load peaks we could theoretically achieve?
  3. How can we minimize the impact of EV charging in practice?

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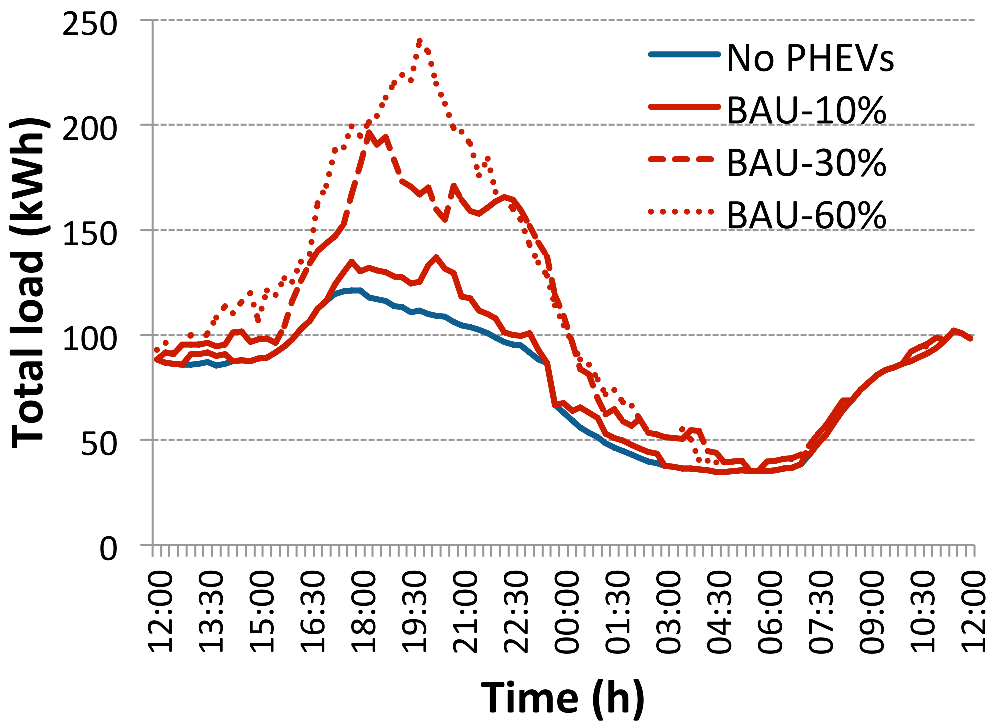
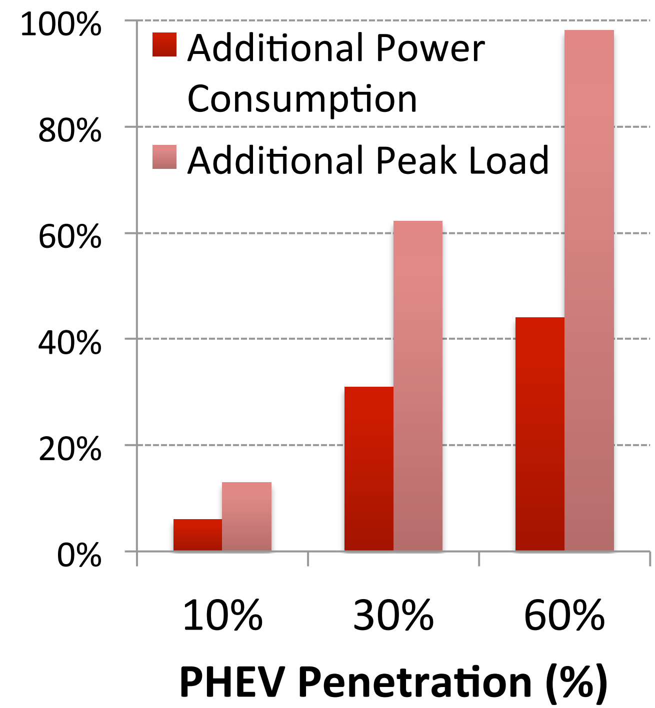
Impact of EV charging

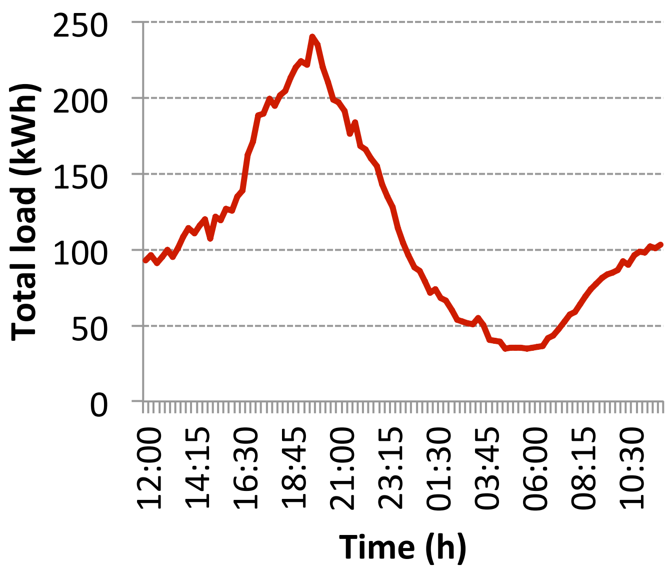
- Sample analysis for 150 homes, x% of them own a PHEV
- BAU = maximally charge upon arrival at home



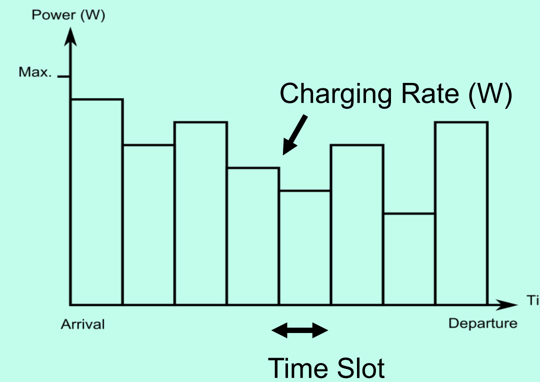


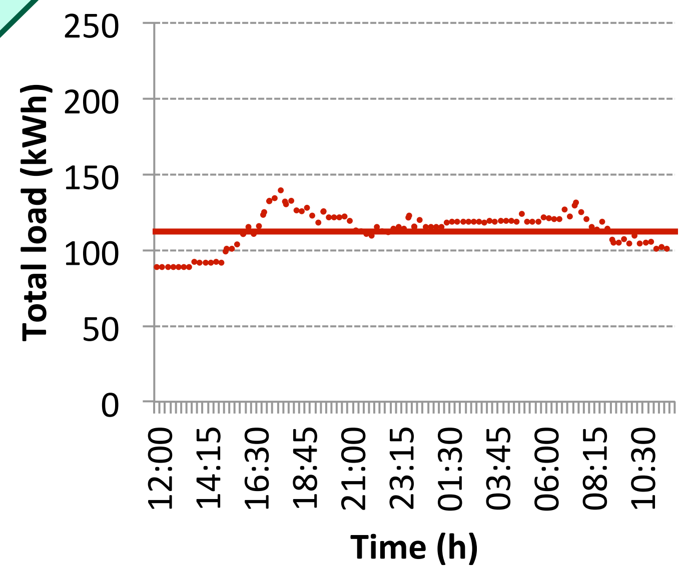
Controlling EV charging?

- Objectives:
  - Reduce peak load
  - Flatten (total) load profile (= reduce time-variability)
  - Avoid voltage violations



Charging schedule





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Smart charging algorithms

Quadratic Programming (QP)

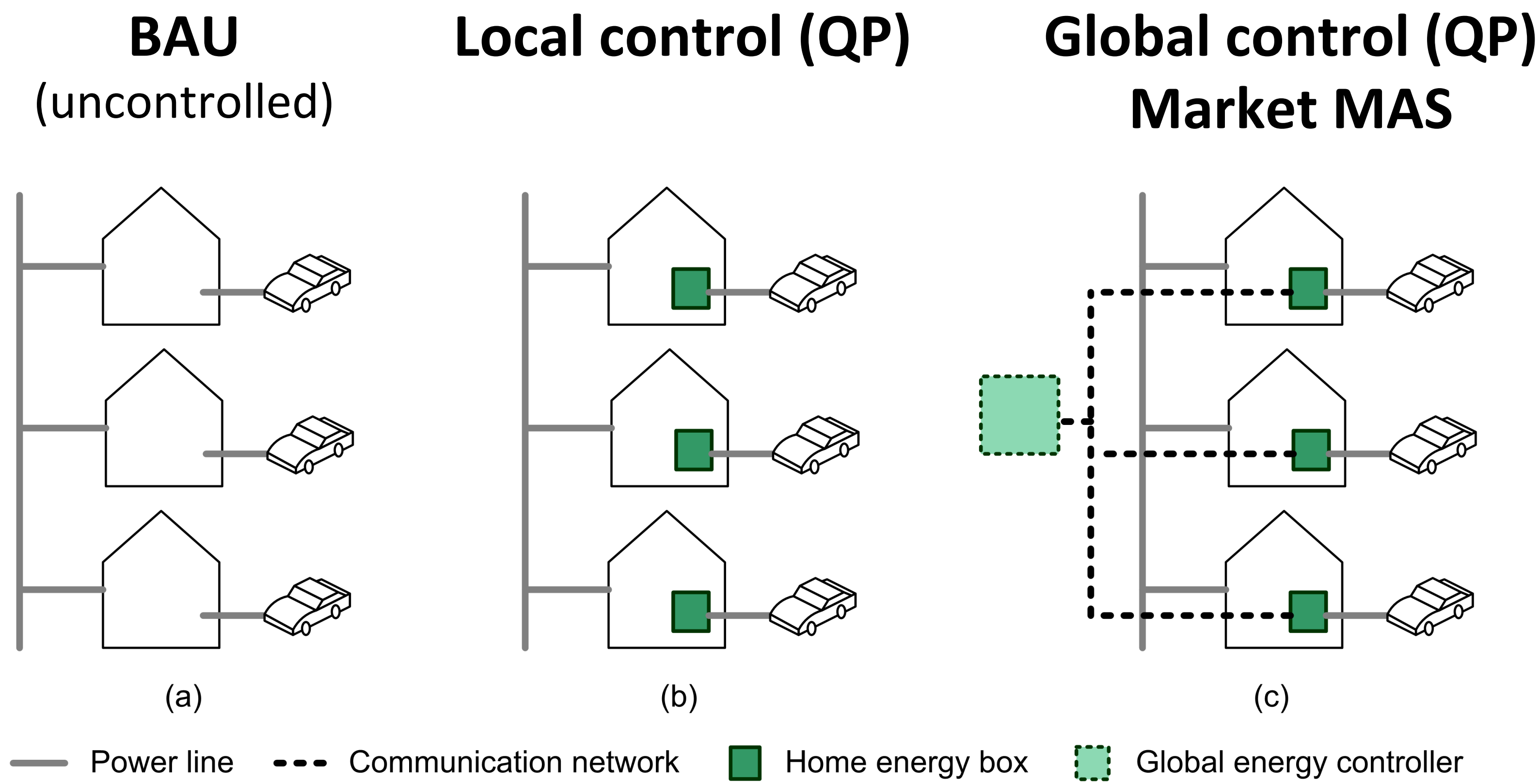
- Offline algorithm
- Planning window
- “Benchmark”
- Three approaches:
  - Local
  - Iterative
  - Global

Multi-Agent System (MAS)

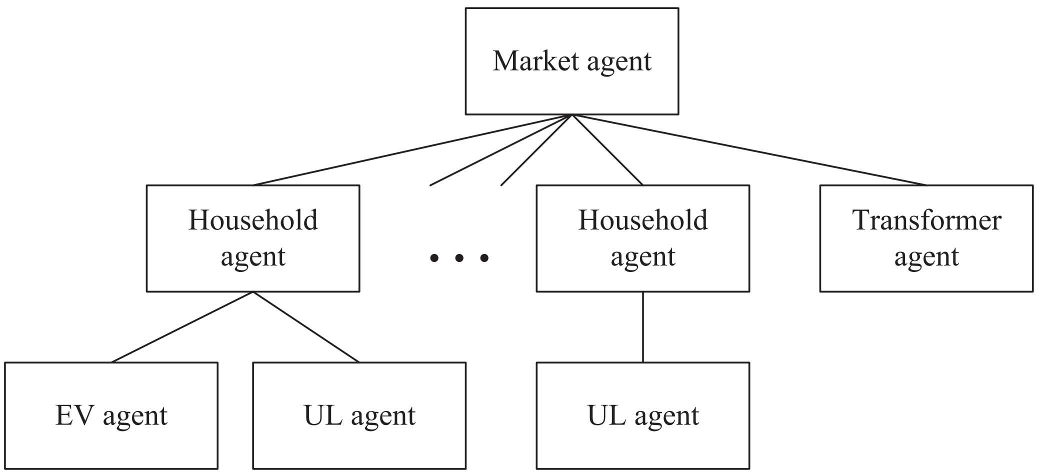
- Online algorithm
- No planning window
  → current time slot info only
  (but EV bidding changes when charging deadline approaches)
- “Realistic”
- Single approach

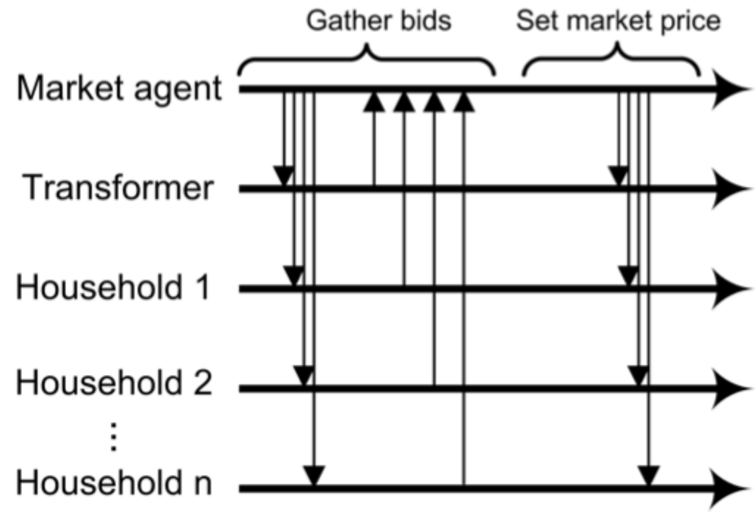
Reference scenario: uncontrolled charging

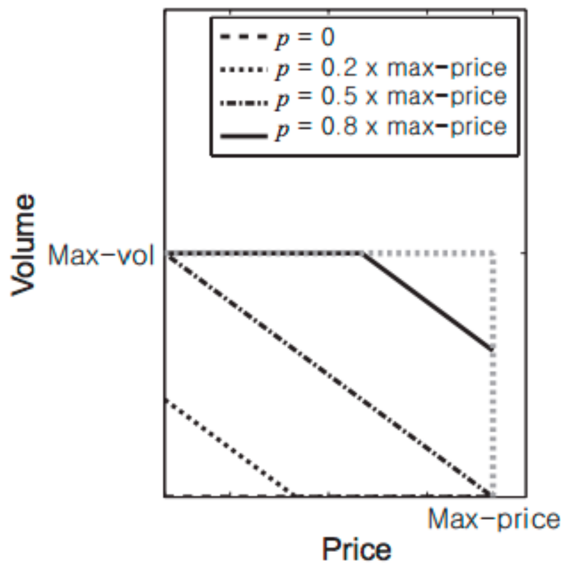
Smart charging: QP



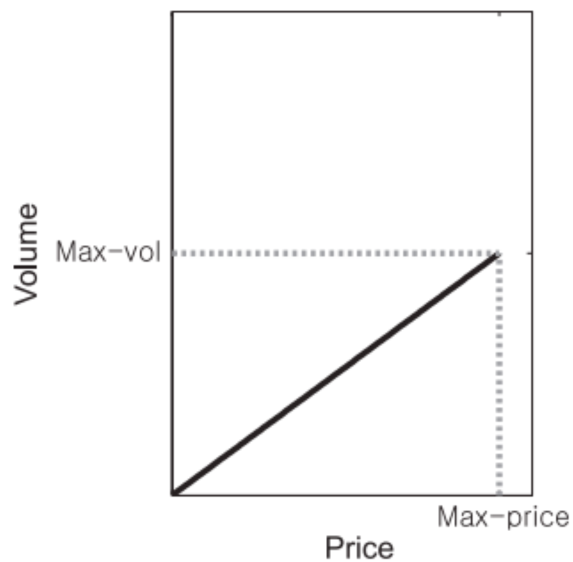
Market-based MAS







(a) EV bidding function



(b) transformer bidding function

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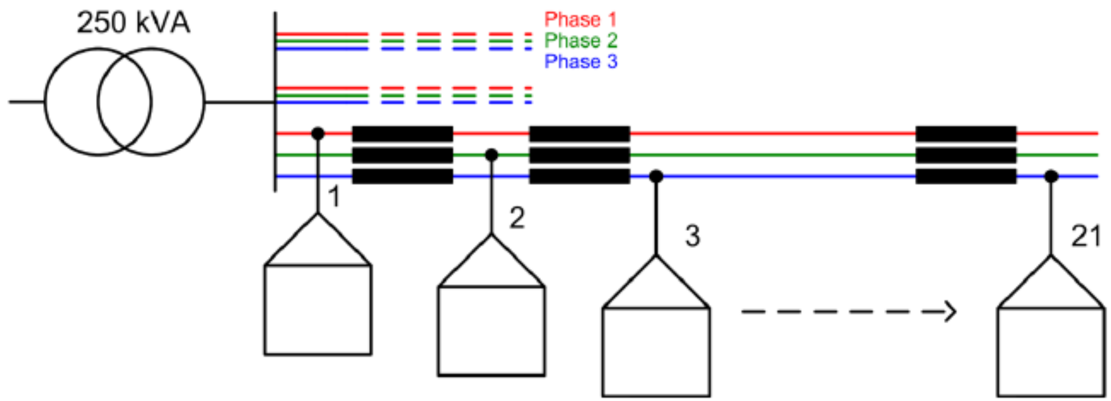
Case study

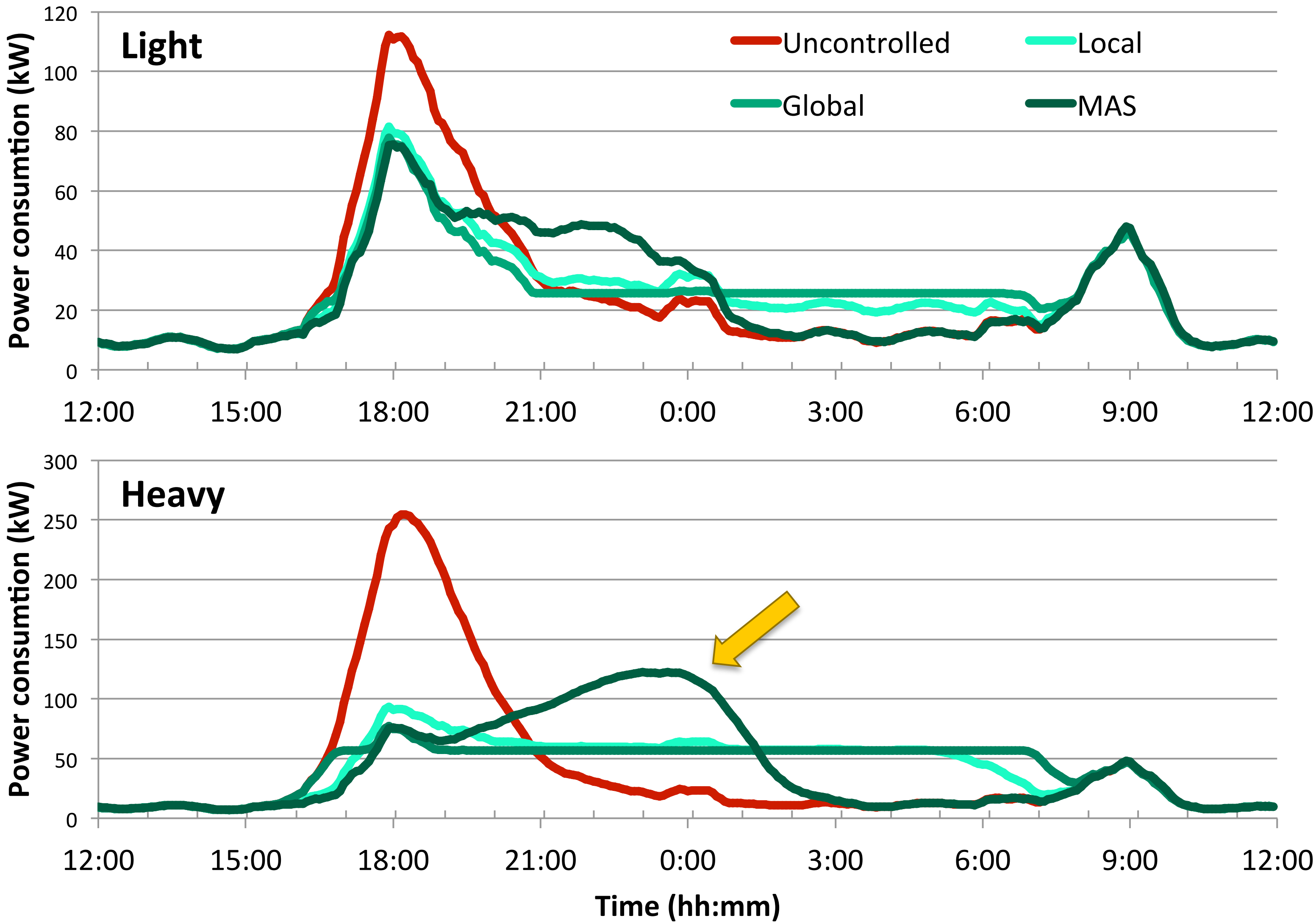
- 63 Households
  - Randomly distributed over 3 phases
  - Spread over 3 feeders



- Electrical vehicles
  - PHEV: 15 kWh battery
  - Full EV: 25 kWh battery
  - Randomized arrivals (~5pm) and departures (~6am)

Scenario	PHEV 3.6 kW	PHEV 7.4 kW	EV 3.6 kW	EV 7.4 kW
Light	4	3	2	1
Medium	10	10	5	4
Heavy	17	16	7	7

Results (1) – Load profiles



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Results (2) – Load peaks & variability

	Peak Load ↘			
Scenario	QP1	QP2	QP3	MAS
Light	29.62%	32.16%	32.16%	32.00%
Medium	53.84%	58.73%	58.73%	53.19%
Heavy	63.76%	70.00%	70.00%	54.04%

	Standard deviation ↘			
Scenario	QP1	QP2	QP3	MAS
Light	35.24%	41.63%	41.94%	25.29%
Medium	55.01%	60.50%	61.88%	34.91%
Heavy	60.22%	63.82%	65.84%	38.80%

QP1 = local QP2 = iterative QP3 = global

Results (3) – Voltage deviations

Table 6. Average number of 5 minute time slots (out of the 288 time slots over the course of the considered one day period) during which voltage deviations exceeding 10% are observed.

Scenario	BAU	QP1	QP2
Light	22.17	3.90	3.31
Medium	38.01	4.52	5.32
Heavy	45.51	3.92	9.30

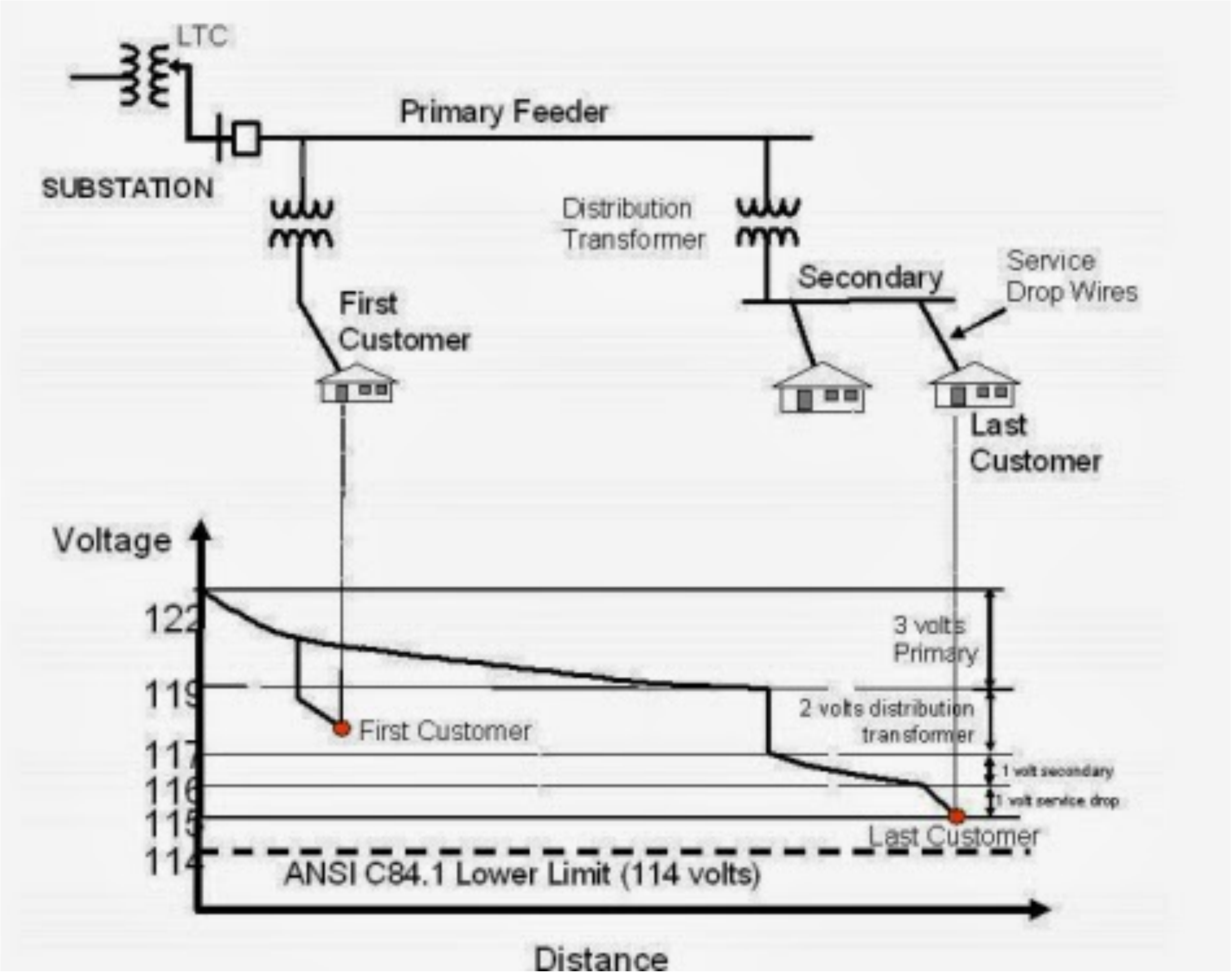
Note: 10 slots ~ 3.4% of the time

Not solved entirely!
(No explicit part of objective function!)

Table 7. Average and maximum magnitude of voltage deviations.

	BAU		QP1		QP2	
Scenario	AVG	MAX	AVG	MAX	AVG	MAX
Light	20%	29%	13%	19%	13%	18%
Medium	29%	60%	13%	22%	13%	20%
Heavy	37%	65%	12%	20%	14%	22%

Voltage deviation?



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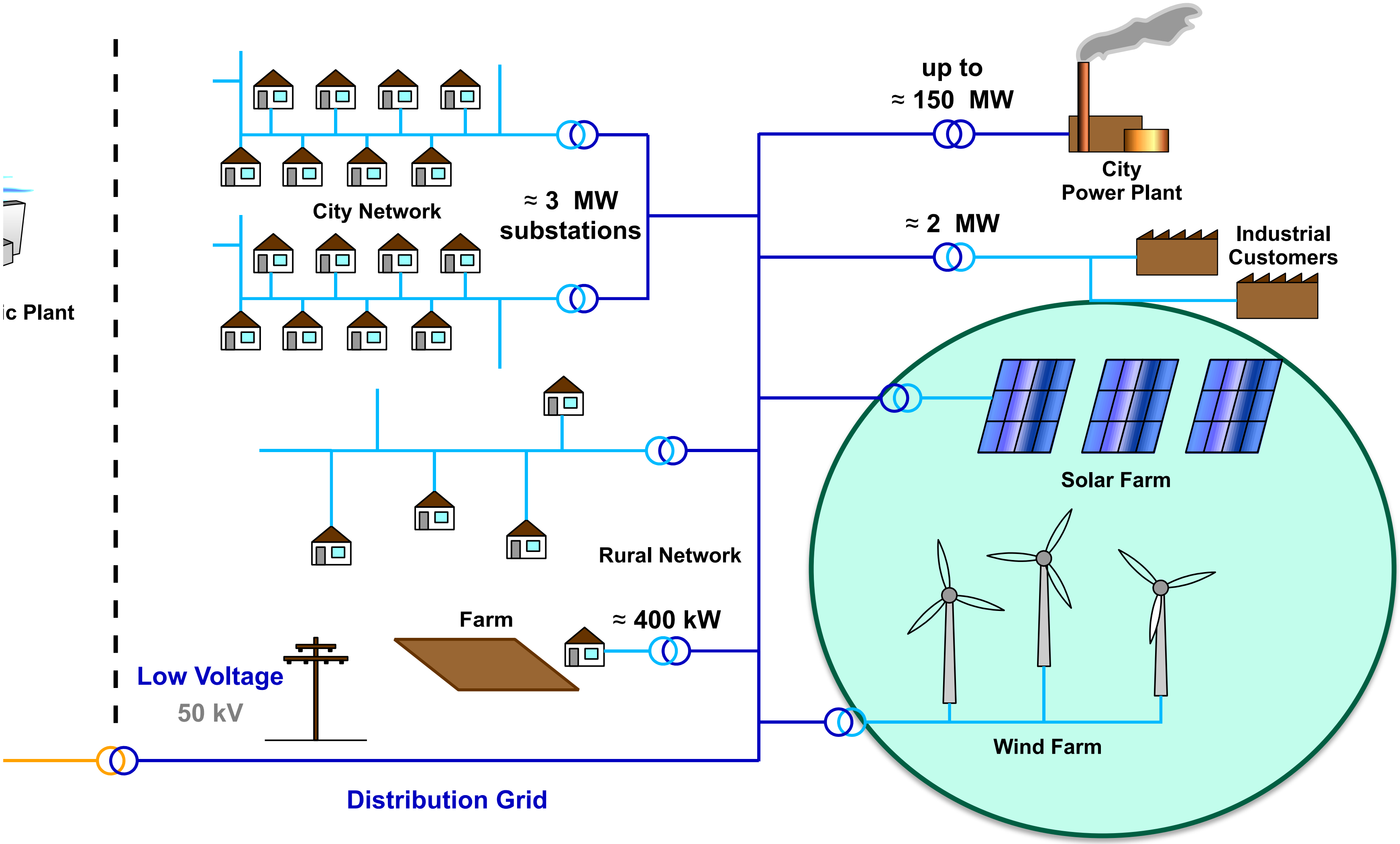
Distributed generation (DG)



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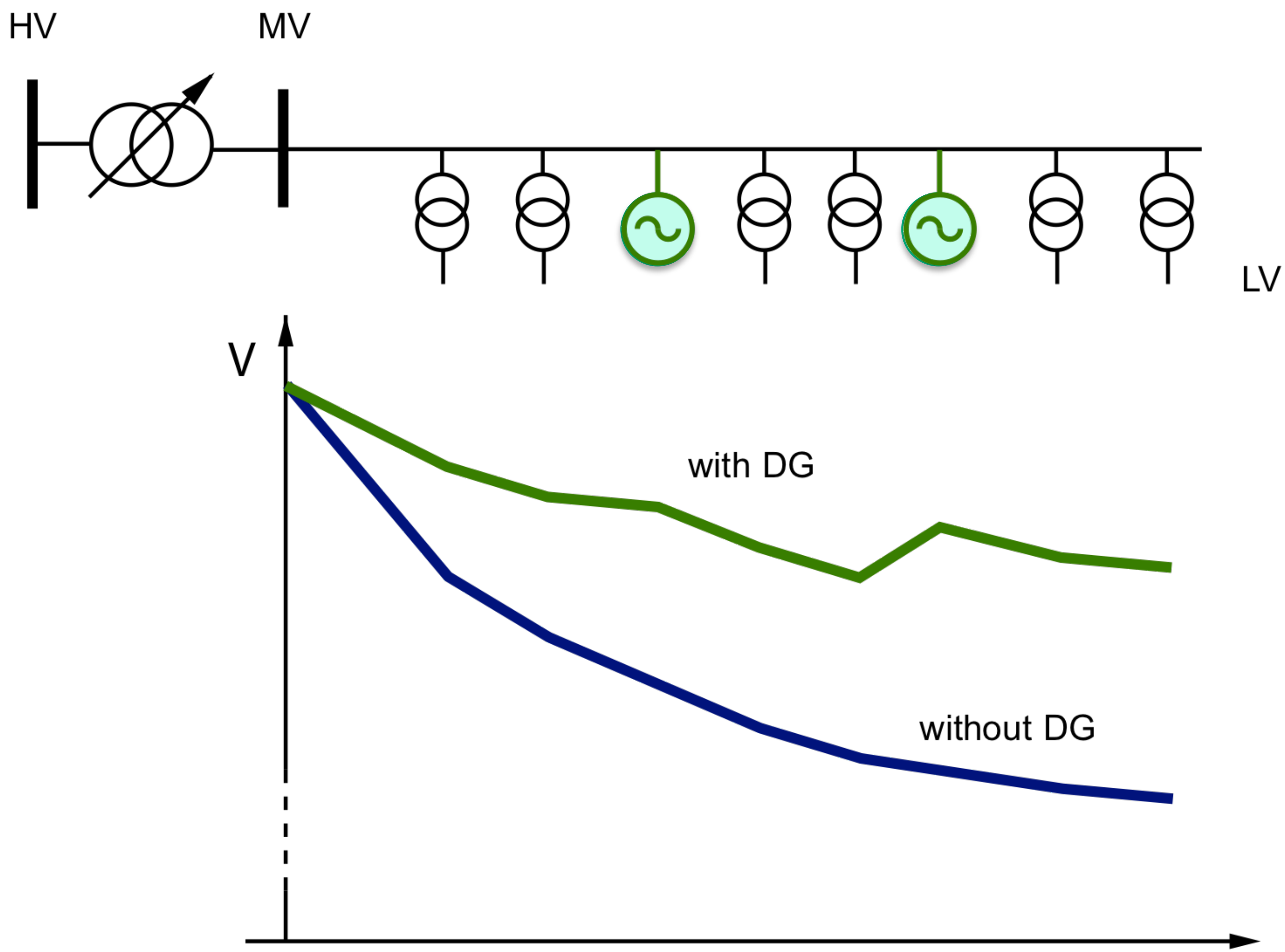
Distributed generation (DG)

- Motivation for DG
  - Use renewable energy sources (RES) ⇒ reduction of CO_2
  - Energy efficiency, e.g., Combined Heat and Power (CHP)
  - Generation close to loads
  - Deregulation: open access to distribution network
  - Subsidies for RES
  - …
- Technologies
  - Wind turbines
  - Photovoltaic systems
  - CHP (based on fossil fuels or RES)
  - Hydropower
  - Biomass
  - …

Technical impact of DG?



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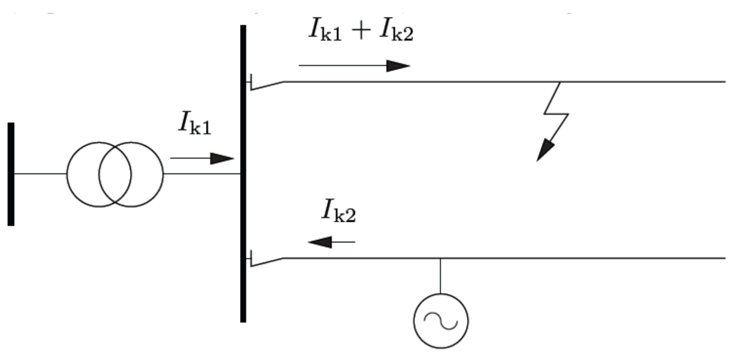
Technical impact of DG?

- Voltage variations
- Islanding?
  - Feeder disconnected from grid
  - DG may be unsafe for people & equipment
  - …
- Power quality
  - Transient voltage variations (during connection/disconnection)
  - Cyclic variations of generator output
  - …
- Protection
  - Increase of fault currents
  - …



Wind turbines

- Horizontal axis
  - Upwind vs downwind
  - Needs to be pointed into the wind
  - High rotational speed (10-22 rpm)
  - Needs a lot of space (cf. 60-90m high; blades 20-40m)

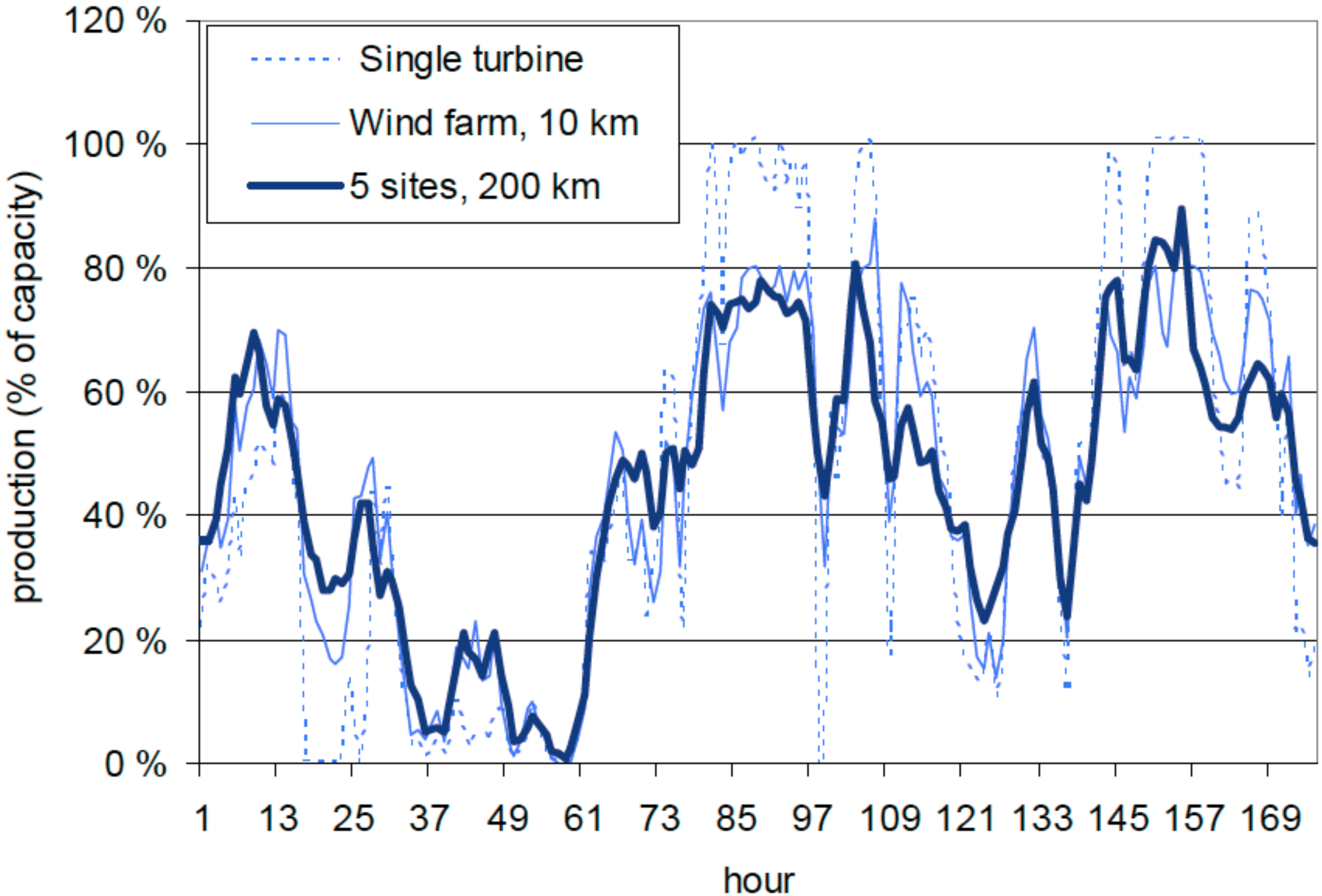
- Vertical axis
  - Omnidirectional
  - No need to point to wind
  - Lower rotational speed
  - Can be closer together

E.g., http://www.inflow-fp7.eu/

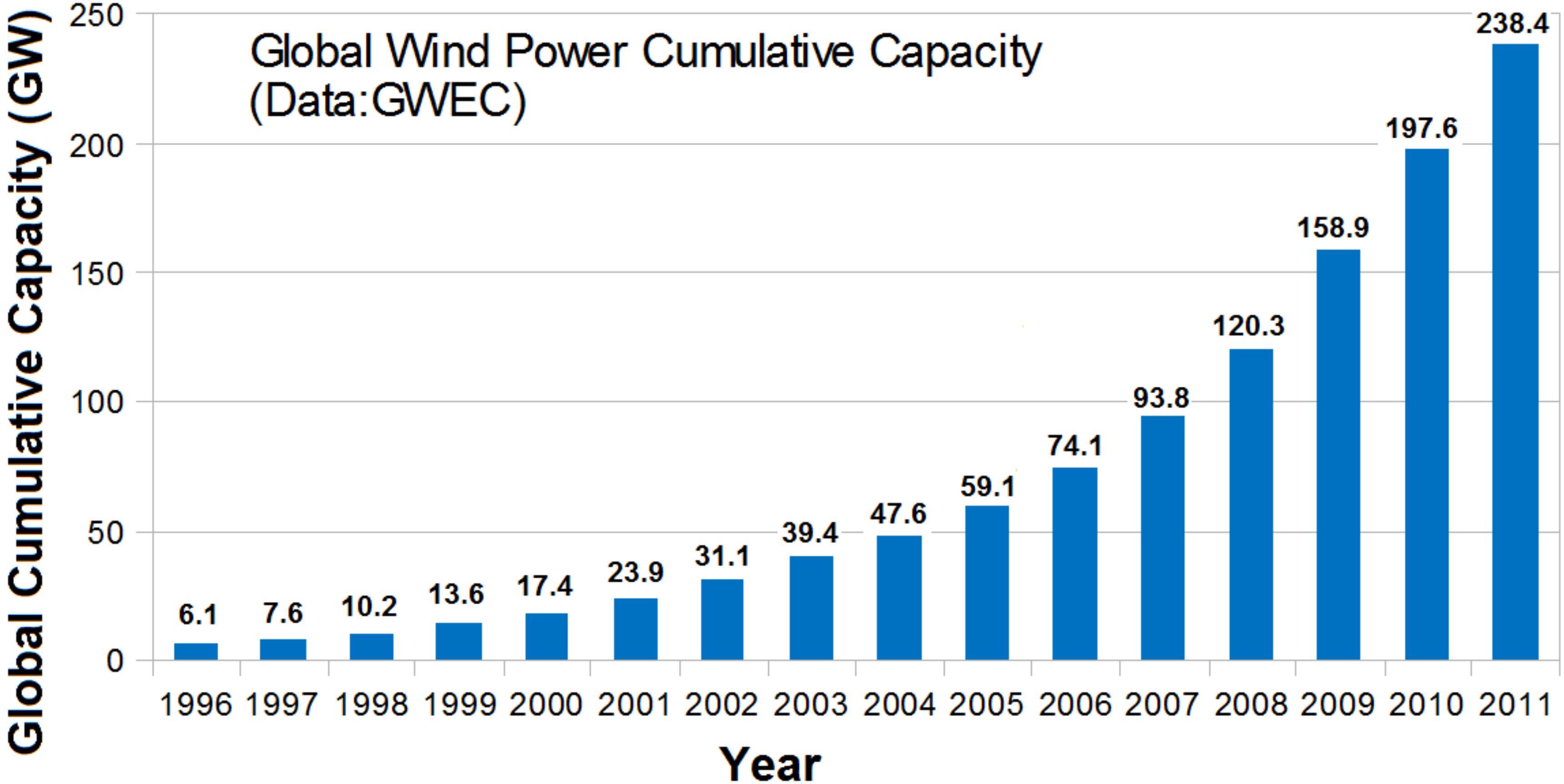
Darrieus

Savonius

A typical wind profile



Worldwide wind power installed capacity



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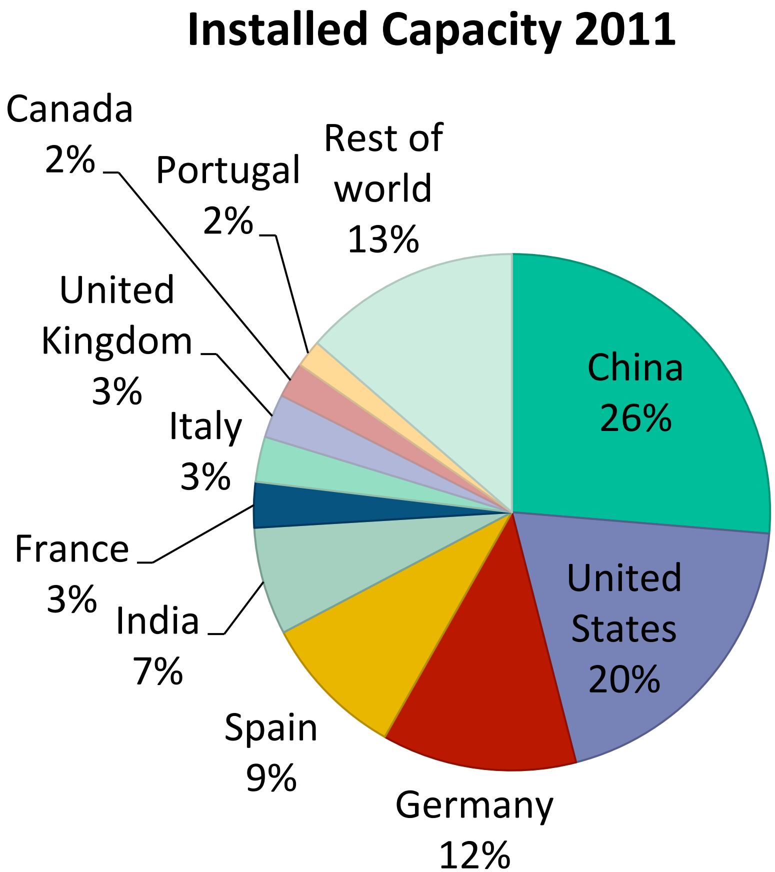
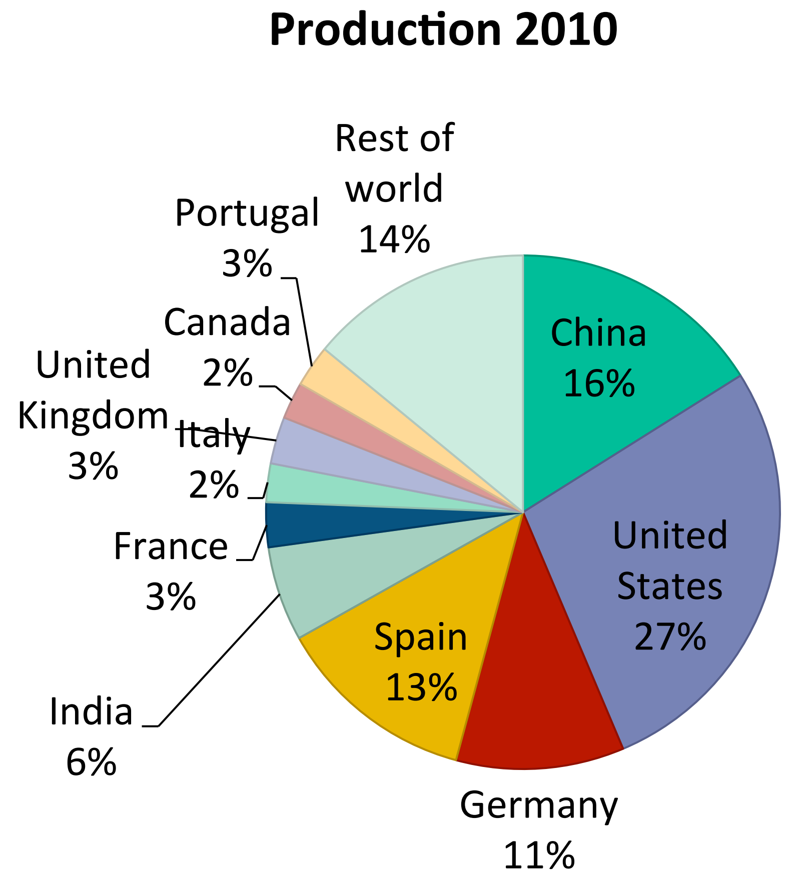
Worldwide wind power capacity & generation

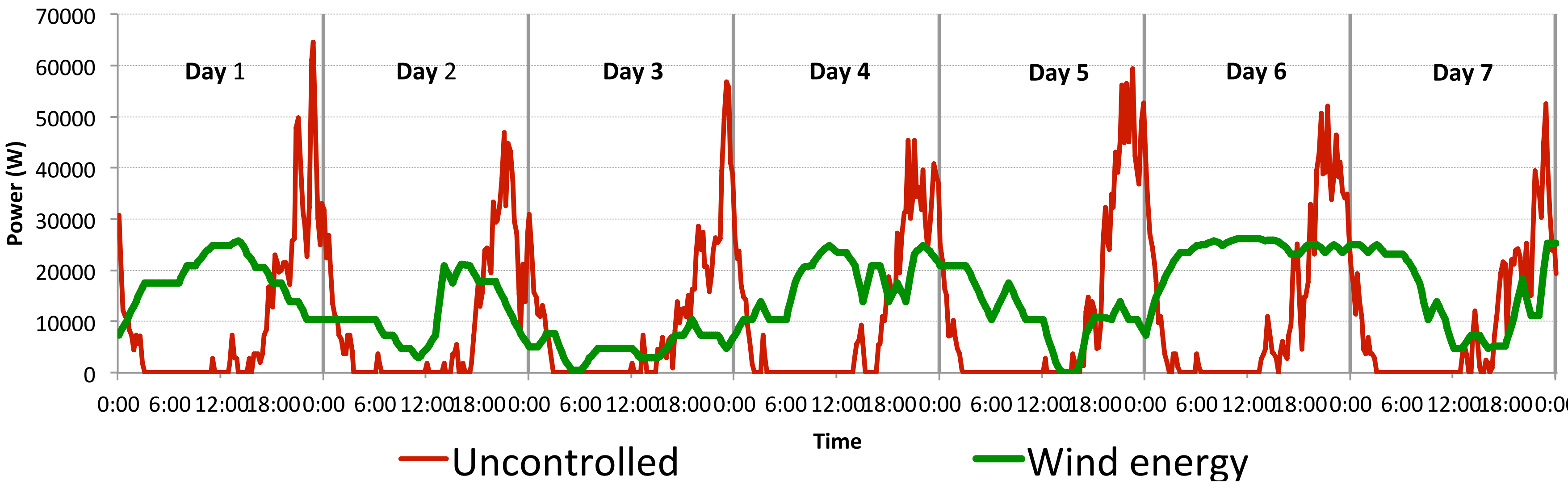




Case Study

*K. Mets, F. De Turck and C. Develder, **"Distributed smart charging of electric vehicles for balancing wind energy"**, in Proc. 3rd IEEE Int. Conf. Smart Grid Communications (SmartGridComm 2012), Tainan City, Taiwan, 5-8 Nov. 2012, pp. 133-138. doi:10.1109/SmartGridComm.2012.6485972*

Wind balancing



- Imbalance between supply and demand
  - Inefficient use of renewable energy sources
  - Imbalance costs
- High peak loads

} Undesirable!

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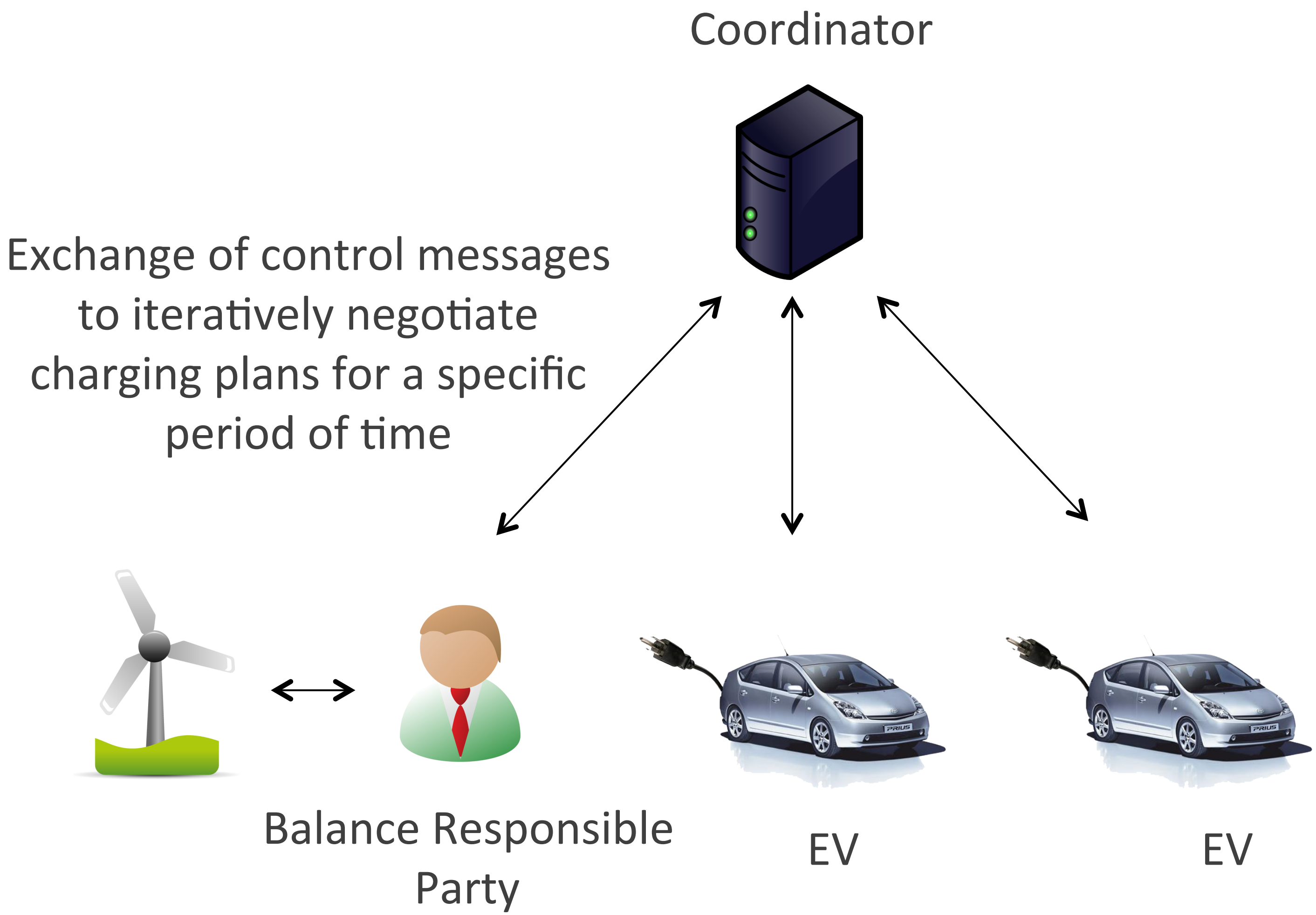
Architecture



Electric vehicle model

- Minimize disutility:
  - Charging schedule variables: x_t^k = charging rate for user k at time t
  - Spread demand over time, preferably at the "preferred charging rate" (p_k), which is the maximum supported charging rate in our case
  - Model behavior/preferences of the subscriber (β_k)

$$D_t^k\left(x_t^k\right) = \beta_k^t \cdot \left(p^k - x_t^k\right)^2 \tag{1}$$

  - Charging schedule for a window of T time slots: minimize disutility

$$\sum_{t=1}^{T} D_t^k\left(x_t^k\right) \tag{2}$$

- Respect energy Requirement: $$\sum_{t=1}^{T_k} x_t^k = E_k \tag{3}$$
  - Vehicle can only be charged between arrival time S_k and departure time T_k

Balance Responsible Party Model

- Imbalance Costs
  - Minimize imbalance costs: cost penalty if supply ≠ demand
  - Supply: wind energy (w_t)
  - Demand: total of all electric vehicles (d_t)
  - Tuning parameter: α
  - Cost function: $C_t\left(d_t\right)=\alpha\cdot\left(w_t-d_t\right)^2$
- For a planning window of T time slots, minimize: $\sum_{t=1}^{T} C\left(d_t\right)$

Centralized Optimization Model

- Based on social welfare maximization
  - Minimize imbalance costs
  - Minimize user disutility
- Objective:

$$\min_{d_t, x_t} \sum_{t=1}^{T} C(d_t) + \sum_{k=1}^{K} \sum_{t=1}^{T} D_t^k(x_t^k)$$

Drawbacks:

1) Privacy: sharing of cost & disutility functions, arrival/ departure info, ...

2) Scalability

- Global constraints:

$$d_t = \sum_{k=1}^{K} x_t^k, \forall t \in \{1, 2, .., T\}$$

- Local constraints:
  - BRP: supply < limit
  - EV: energy & time constraints

Distributed optimization model

- Move demand-supply constraint into objective, w/ Lagrange multiplier λ_t

$$\sum_{t=1}^{T} C\left(d_t\right) + \sum_{k=1}^{K}\sum_{t=1}^{T}\left(D_t^k\left(x_t^k\right) + \lambda_t\left(x_k^t - d_t\right)\right)$$

- Notice: Objective function is separable into K+1 problems that can be solved in parallel *(assuming λ_t are given)*

1 BRP problem

$$\boxed{\sum_{t=1}^{T}\left(C\left(d_t\right) - \lambda_t d_t\right)} + \boxed{\sum_{k=1}^{K}\sum_{t=1}^{T}\left(D_t^k(x_t^k) + \lambda_t x_t^k\right)}$$

K subscriber problems

- Iteratively update pricing vector…

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Distributed optimization model scheme:

1. Coordinator distributes virtual prices
2. BRP solves local problem } in parallel
3. Subscribers solve local problem } in parallel
4. Coordinator collects schedules:
   - **BRP**: $d^i = [d_1^i, d_2^i, ..., d_T^i]$
   - **EVs**: $x^{k,i} = [x_1^{k,i}, x_2^{k,i}, ..., x_T^{k,i}]$
5. Coordinator updates virtual prices:

$$\lambda_t^{i+1} = \lambda_t^i + \gamma \cdot \left[\sum_{k=1}^{K} x_t^{k,i} - d_t^i \right]$$

6. Repeat until demand = supply

Case study: Assumptions

- Wind energy supply ≈ EV energy consumption
  - Energy supply = 6.8 MWh
- 100 Electric vehicles
  - Battery capacity: 10 kWh battery
  - Maximum charge power: 3.68 kW
  - Arrivals & departures: statistical model
  - Charging at home scenario
- Time
  - Simulate 4 weeks
  - Time slots of 15 minutes
  - Planning window of 24 hours

Case study: Algorithms

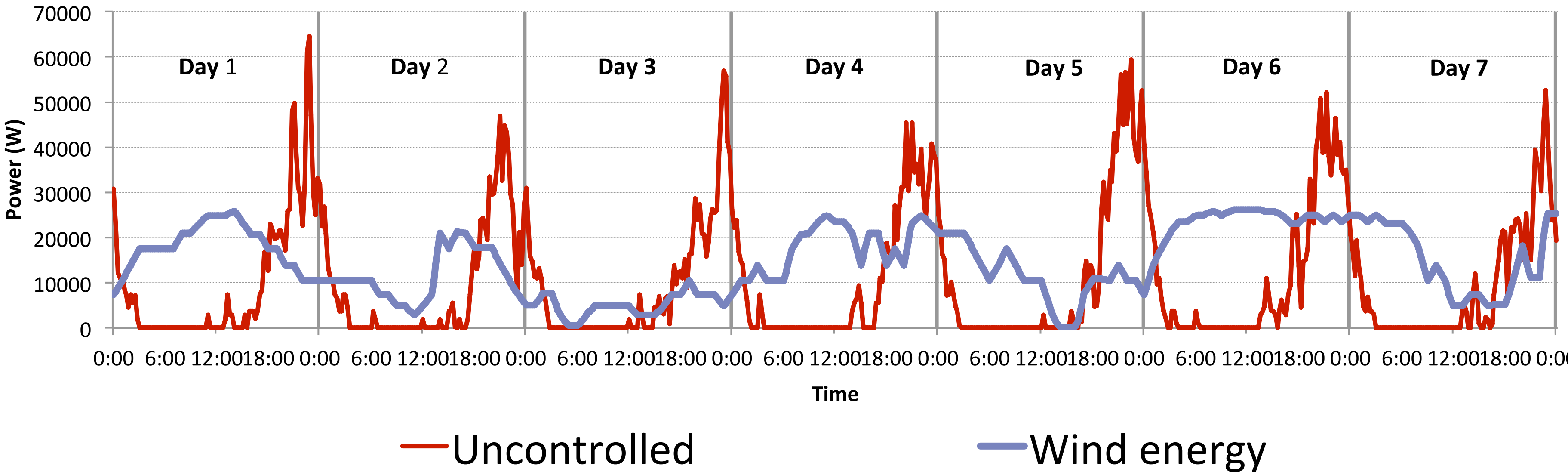
- **Uncontrolled business as usual (BAU)**
  - EV starts charging upon arrival
  - EV stops charging when state-of-charge is 100%
  - No control or coordination

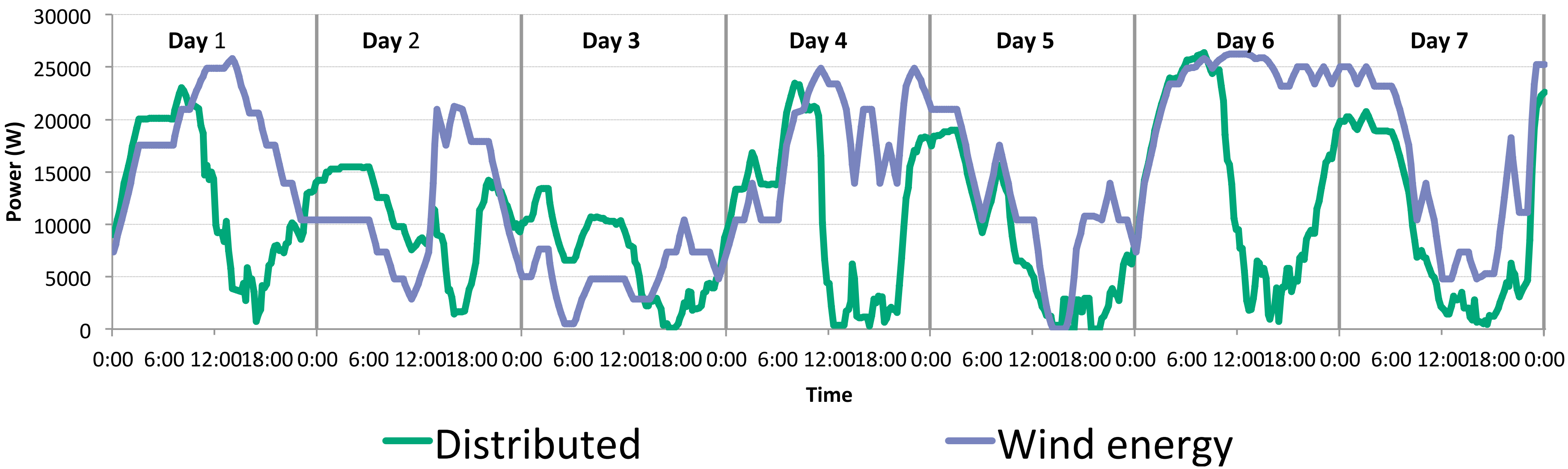
- **Distributed algorithm**
  - Executed at the start of each time slot

- **“Ideal world” benchmark**
  - Offline all-knowing algorithm determines schedules for ALL sessions
  - No EV disutility function → maximum flexibility
  - Objective:

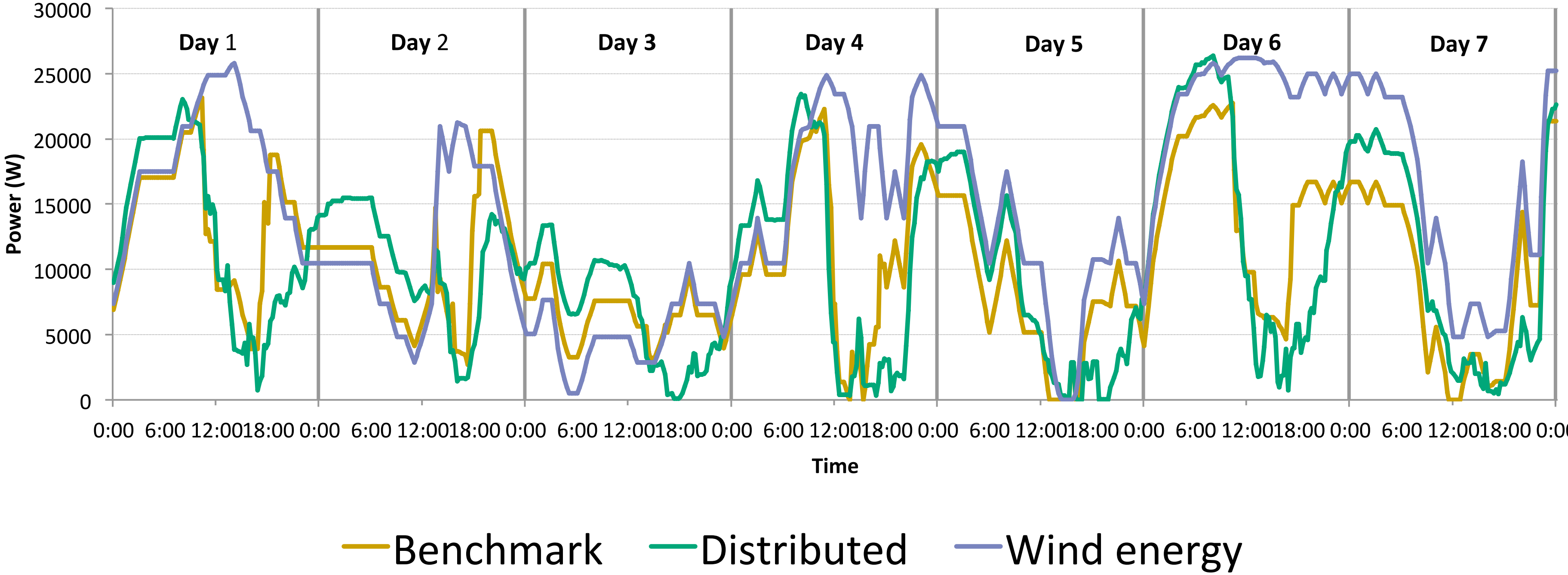
$$\min \sum_{t=1}^{S} \left(w_t - \sum_{k=1}^{K} x_t^k \right)^2$$

Results: Uncontrolled BAU vs. Distributed





Results: Distributed vs. Benchmark



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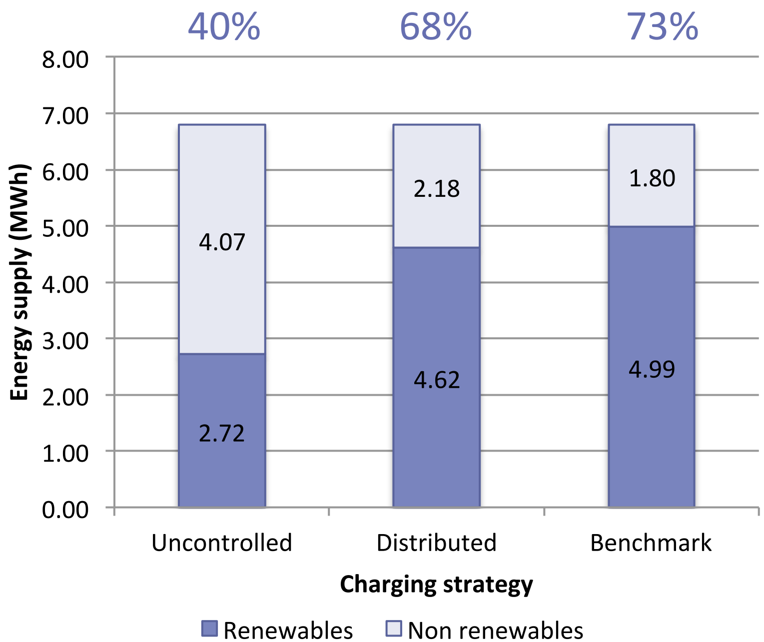
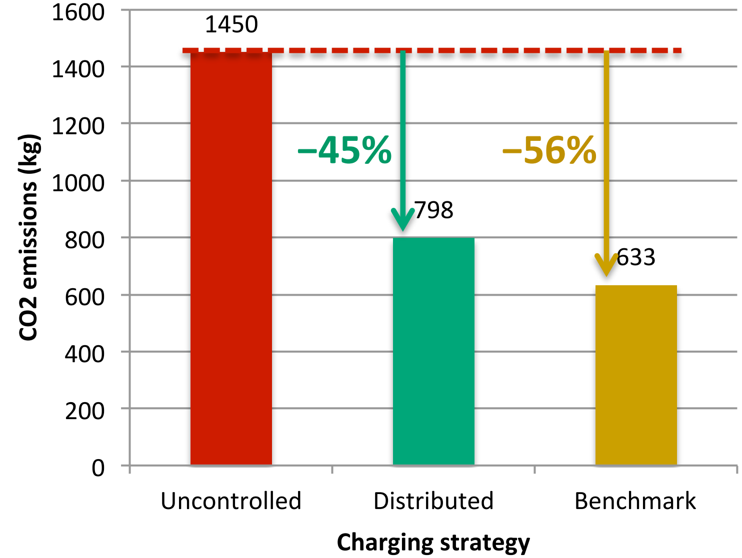
INTEC

Results: Energy Mix





Renewables: 7.4 CO2 g/kWh
Non Renewables: 351.0 CO2 g/kWh

- Total energy consumption ≈ 6.8 MWh
- Substantial increase in the use of renewable energy
- Reduced CO_2 emissions

Conclusions

- **Objective**: balance wind energy supply with electric vehicle charging demand
- **Method**: Distributed coordination algorithm in which participants exchange virtual prices and energy schedules
- **Performance**: Distributed coordination significantly better than BAU, close to "ideal world" benchmark
  - Increased usage of renewable energy sources
  - Reduction of CO_2 emissions

Outline

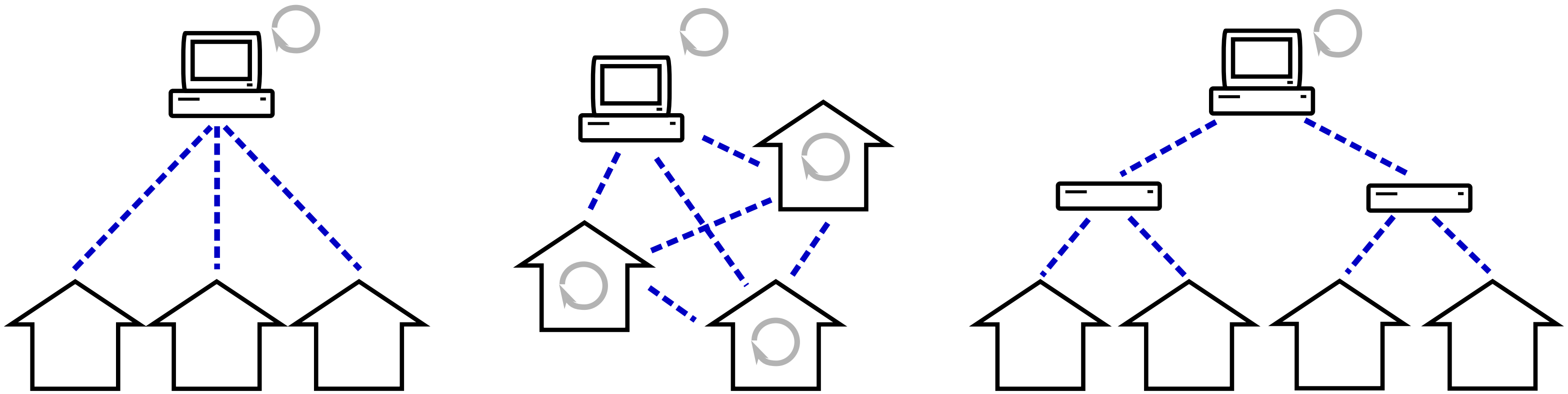
1. Introduction
2. Example 1: Peak shaving
3. Example 2: Wind balancing
4. DR algorithms for EV charging
5. Tools to study EV charging
6. Wrap-up

Outline

*K. De Craemer, **"Ch.3: Algorithms for demand response of electric vehicles"**, in: "Event-Driven Demand Response for Electric Vehicles in Multi-aggregator Distribution Grid Settings", Ph.D. Thesis, KU Leuven, Jul. 2014*

Strategies for DR

Optimization



Centralized | Distributed | Aggregate & dispatch

Centralized

- Approximate DP
- Stochastic programming
- Iterative local search to solve (M)ILP
- …

Distributed

- Game theory
- Distributed optimization
- …

> E.g., dual decomposition

Aggregate & dispatch

- Ranking, MPC
- State-bin modeling
- Market-based
- …

Figure adapted from [K. De Craemer, 2014]

Strategies for DR: Scalability vs optimality

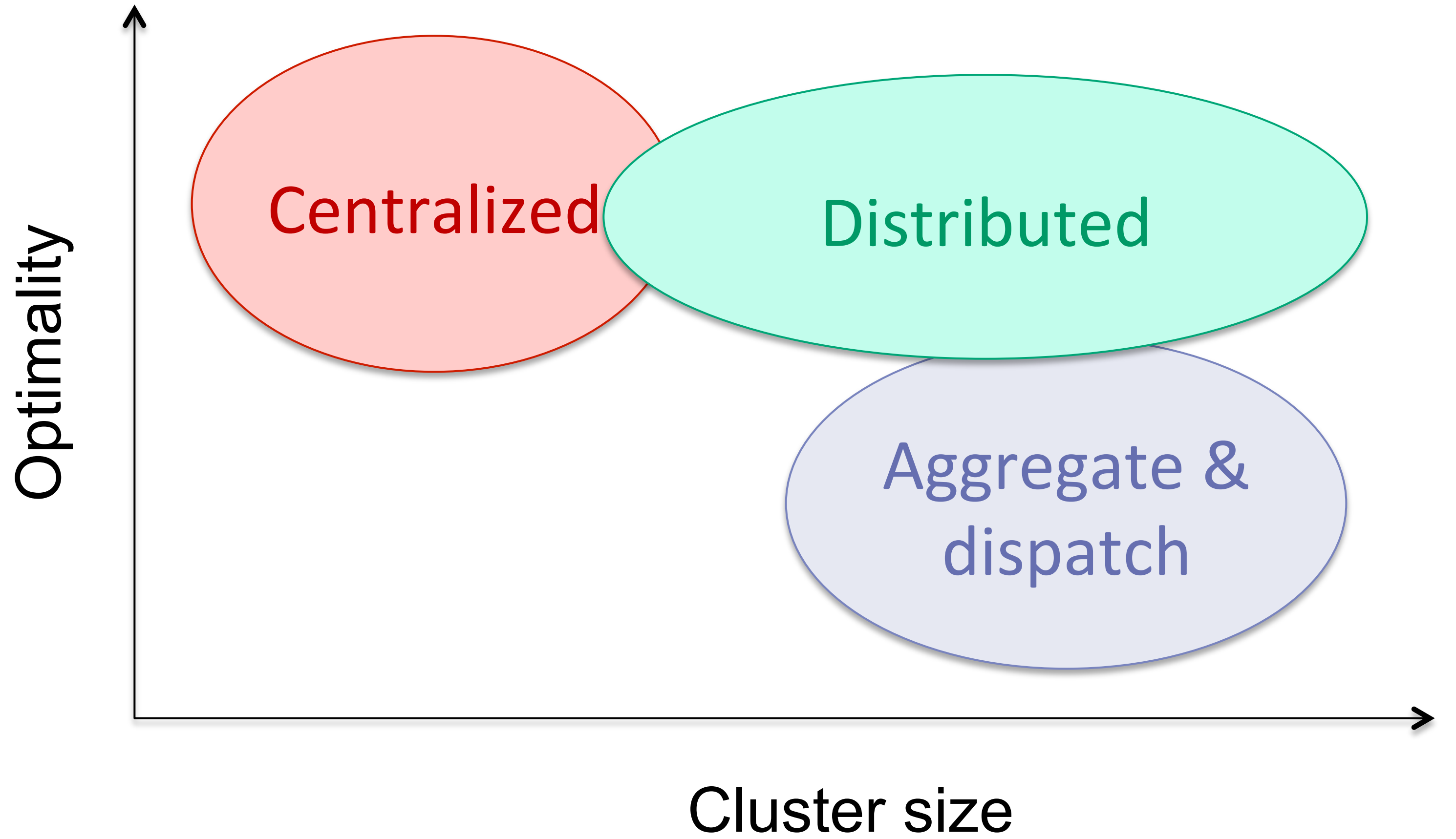
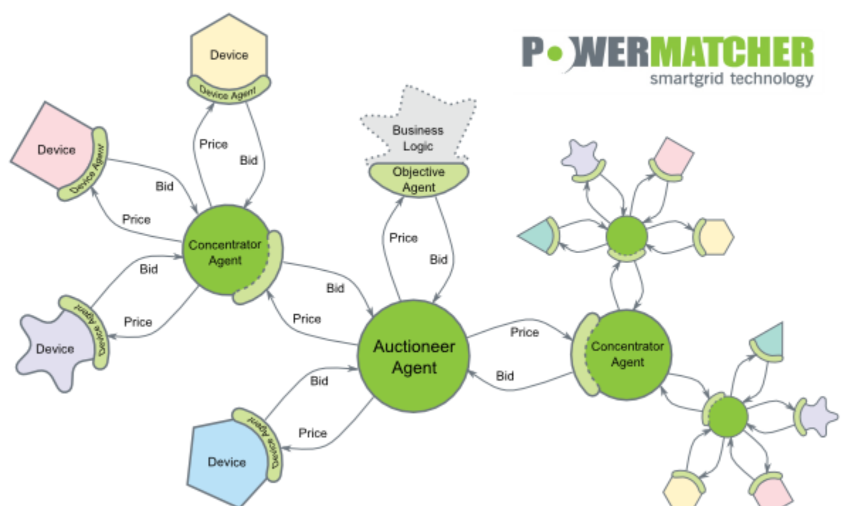


Figure adapted from [K. De Craemer, 2014]

Multi-agent systems (MAS)

- Agent
  = takes independent action to achieve its design objectives
  ≠ told explicitly what to do exactly
- Multi-agent
  = interacting agents, via message exchange
  = cooperating/coordinating/negotiating agents
- Example: PowerMatcher = market-based agent system



C. Develder, et al., "Distributed smart charging of electrical vehicles"

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*K. Mets, J. Aparicio and C. Develder, **"Combining power and communication network simulation for cost-effective smart grid analysis"**, IEEE Commun. Surveys Tutorials, Vol. PP, 2014, pp. 1-26.. doi:10.1109/SURV.2014.021414.00116*

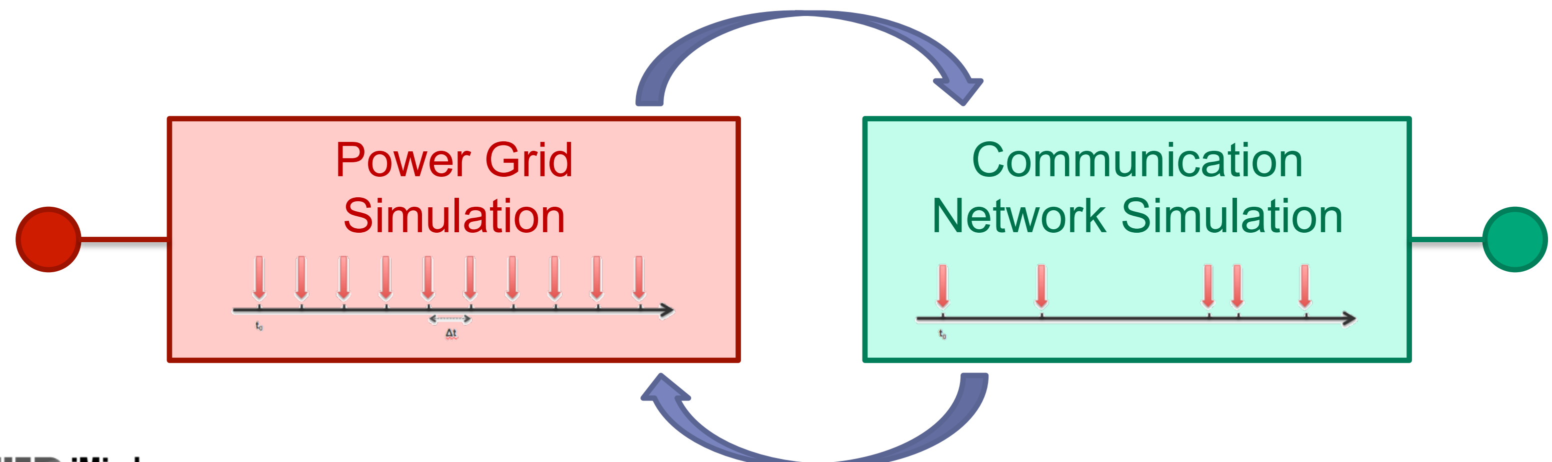
Problem Statement

- Simulators are already used in the two domains:
  - **Communication** network engineering
  - **Power** engineering

ns-2 / ns-3 | OMNeT++ | …

OpenDSS | Matlab tools | …

- In a **co-simulation** approach, power & communication are loosely coupled
  - Requires careful synchronisation
  - Drawback: no integration of tools



C. Develder, et al., "Distributed smart charging of electrical vehicles"

Challenge for co-simulation: Synchronisation

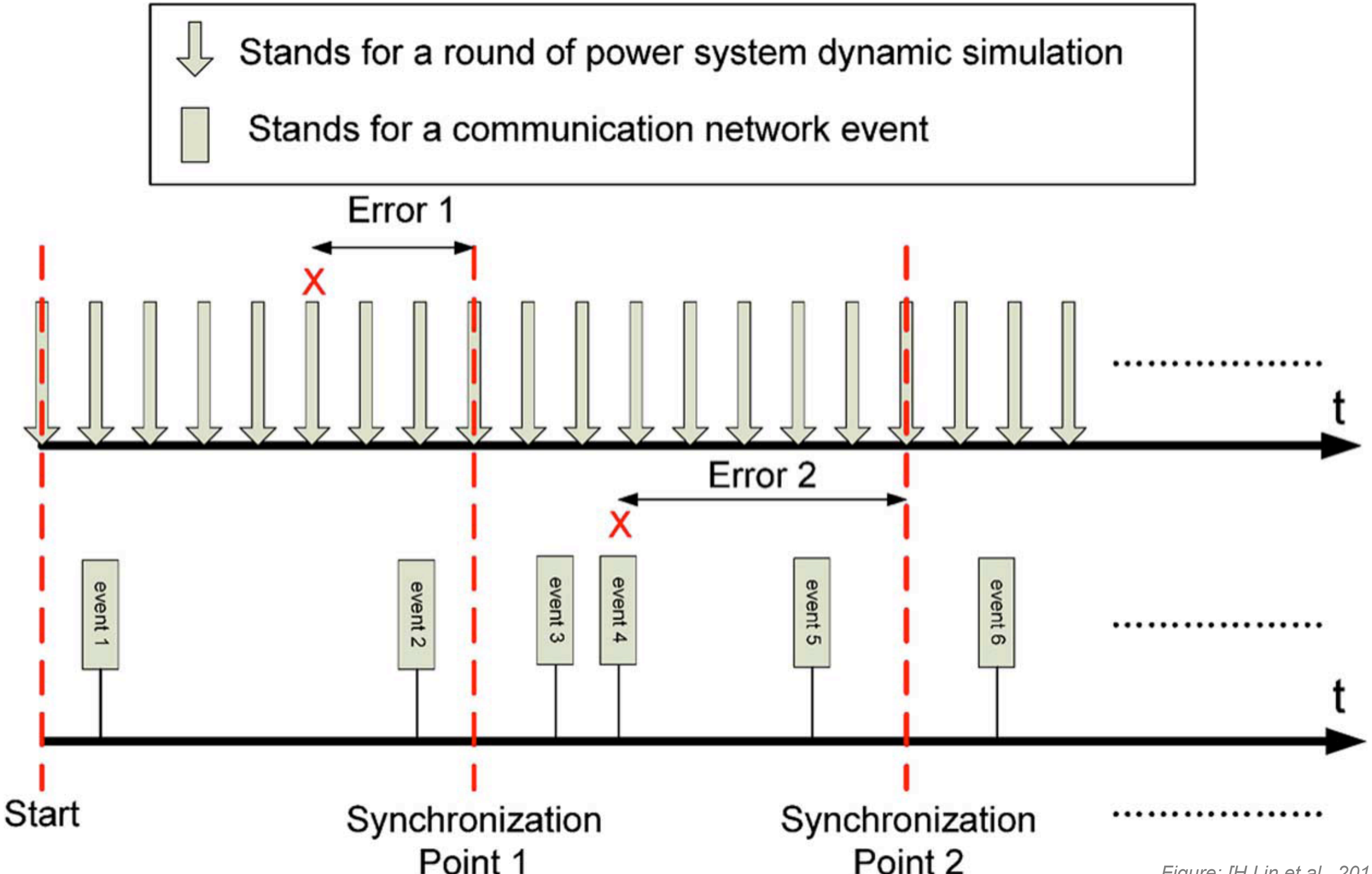
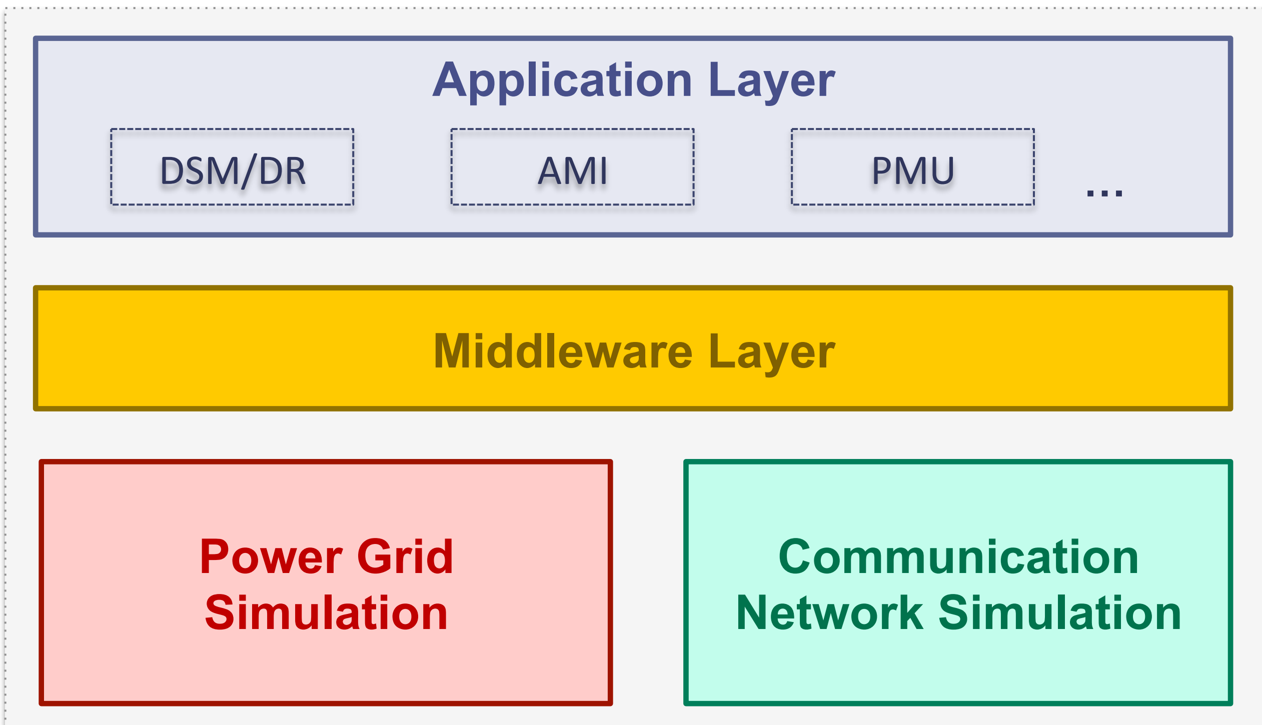


Figure: [H.Lin et al., 2012]

Our solution

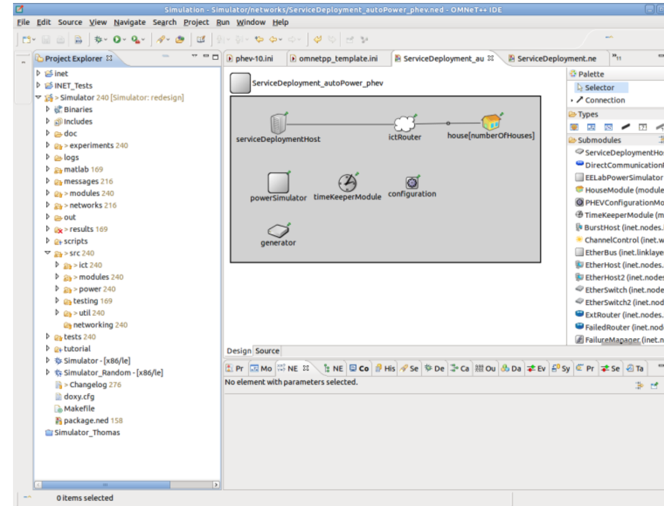
Integrated (combined) power grid and communication network simulation

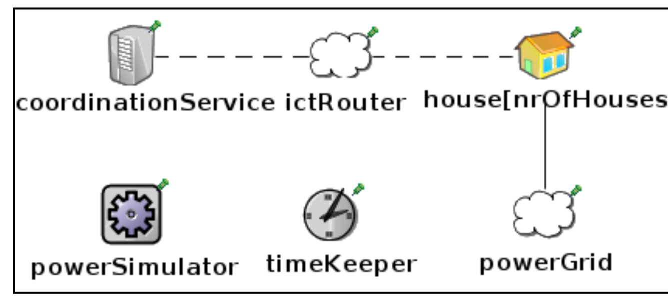
→ Large scale smart grid simulations

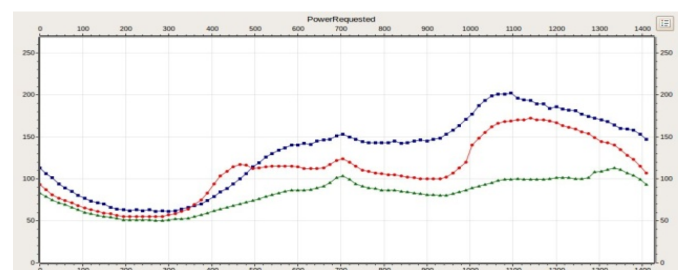


OMNeT++

- Discrete Event Simulator:
  - Modular, Scalable, Cluster support
  - Models for communication networks
  - Integrated in Eclipse
  - Random Data Generation
  - Graphical representations
  - Data logging, presentation, processing, etc.
  - Open source
  - ….







- Custom Components:
  - Electric components: loads, generators, etc.
  - ICT components: smart devices, coordination services, …

C. Develder, et al., "Distributed smart charging of electrical vehicles"

Power Flow Simulator

- Support for **radial distribution grid** topologies.
- Model based on **Fast Harmonic Simulation** Method [1].
- Model implemented in **MATLAB** and integrated in simulator.
- Uses an Iterative forward/backward sweep method:

INPUT:

- Power demand (Watt) at each node at time *t*.
- Phase to which each node is connected

LOOP:

Backward sweep

- Determines currents in every node, based on known voltages in each node.
- Currents in all network branches are determined.

Forward sweep

- Determines voltage at every node

Compare voltages with the voltages in the previous iteration.

If difference below a certain threshold:

Stop iterations.

Else

Continue iterations.

[1] L. Degroote, L. Vandevelde, and B. Renders, "Fast harmonic simulation model for the analysis of network losses with converter-connecter distributed generation", *Electric Power System Research*, vol. 80, pp. 1332-1340, 2010.

Communication Network Models

- **INET Framework**:

  Open source communication network simulation package for OMNeT++

Layer	Protocol
Transport	TCP
	UDP
Network	IPv4
	IPv6
Link	Ethernet
	802.11 (WiFi)
	PPP

INET FRAMEWORK

Implemented as OMNeT++ modules.
→ Simulate different technologies

- … or basic **OMNet++ message framework**:

  No specific protocol or physical layers are simulated

  →Reduced overhead compared to INET

Simulator Configuration

Nodes

Implementation of ICT and/or power components
The nodes and interconnections between nodes form the power grid and communication network that form the simulated smart grid.

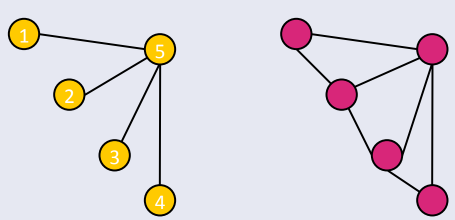
Network Description File

List of used modules

- Electrical network model
- Communication network
- Smart devices

Topology

- Electrical
- Communication



INI File

Node parameters

- Node type
- Generator capacity
- Battery charge rate
- ...

Simulation parameters

- # houses, # devices, …
- Communication technologies
- Device properties
- Control algorithms

Defining input files

- E.g., load profiles

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Take-away points

- Challenges for the grid:
  - Increased renewable energy sources + distributed into LV/MV network
  - Increase of load (e.g., EVs)
- Penetration of EVs:
  - HEV vs BEV
  - Need for peak shaving and/or balancing
  - Benefit of V2G?
- DR algorithms
  - Distributed vs centralized
  - Agent-based systems
- Open questions → what-if analysis required: simulation tool!

Future & ongoing work

- Communication network architecture
  - C-DAX concept: generic smart grid middleware
  - Hierarchical architecture, e.g., using data aggregators to reduce communication overhead
  - Communication network requirements, impact of communication problems, etc.
- Algorithm development
  - Stochastic behavior
  - Multiple balancing zones
  - Vehicle-to-grid support

Thank you … any questions?

Thank you … any questions?

Prof. Chris Develder
chris.develder@intec.ugent.be
Ghent University – iMinds

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